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Methods for External Event Screening Quantification: Risk Methods Integration and Evaluation Program (RMIEP) Methods Development

Prepared by
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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

In this report, the scoping quantification procedures for external events in probabilistic risk assessments of nuclear power plants are described. External event analysis in a PRA has three important goals:

1. The analysis should be complete in that all events are considered.

2. By following some selected screening criteria, the more significant events are identified for detailed analysis.

3. The selected events are analyzed in depth by taking into account the unique features of the events: hazard, fragility of structures and equipment, external-event initiated accident sequences, etc.

Based on the above goals, external event analysis may be considered as a three-stage process:

Stage I: Identification and Initial Screening of External Events

Stage II: Bounding Analysis

Stage III: Detailed Risk Analysis

In the present report, first, a review of published PRAs is given to focus on the significance and treatment of external events in full-scope PRAs. Except for seismic, flooding, fire, and extreme wind events, the contributions of other external events to plant risk have been found to be negligible. Second, scoping methods for external events not covered in detail in the NRC's PRA Procedures Guide are provided. For this purpose, bounding analyses for transportation accidents, extreme winds and tornadoes, aircraft impacts, turbine missiles, and chemical release are described.

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FOREWORD

LaSalle Unit 2 Level III Probabilistic Risk Assessment

In recent years, applications of Probabilistic Risk Assessment (PRA) to nuclear power plants have experienced increasing acceptance and use, particularly in addressing regulatory issues. Although progress on the PRA front has been impressive, the usage of PRA methods and insights to address increasingly broader regulatory issues has resulted in the need for continued improvement in and expansion of PRA methods to support the needs of the Nuclear Regulatory Commission (NRC).

Before any new PRA methods can be considered suitable for routine use in the regulatory arena, they need to be integrated into the overall framework of a PRA, appropriate interfaces defined, and the utility of the methods evaluated. The LaSalle Unit 2 Level III PRA, described in this and associated reports, integrates new methods and new applications of previous methods into a PRA framework that provides for this integration and evaluation. It helps lay the bases for both the routine use of the methods and the preparation of procedures that will provide guidance for future PRAs used in addressing regulatory issues. These new methods, once integrated into the framework of a PRA and evaluated, lead to a more complete PRA analysis, a better understanding of the uncertainties in PRA results, and broader insights into the importance of plant design and operational characteristics to public risk.

In order to satisfy the needs described above, the LaSalle Unit 2, Level III PRA addresses the following broad objectives:

1) To develop and apply methods to integrate internal, external, and dependent failure risk methods to achieve greater efficiency, consistency, and completeness in the conduct of risk assessments;

2) To evaluate PRA technology developments and formulate improved PRA procedures;

3) To identify, evaluate, and effectively display the uncertainties in PRA risk predictions that stem from limitations in plant modeling, PRA methods, data, or physical processes that occur during the evolution of a severe accident;

4) To conduct a PRA on a BWR 5, Mark II nuclear power plant, ascertain the plant's dominant accident sequences, evaluate the core and containment response to accidents, calculate the consequences of the accidents, and assess overall risk; and finally

5) To formulate the results in such a manner as to allow the PRA to be easily updated and to allow testing of future improvements in methodology, data, and the treatment of phenomena.

The LaSalle Unit 2 PRA was performed for the NRC by Sandia National Laboratories (SNL) with substantial help from Commonwealth Edison (CECo) and its contractors. Because of the size and scope of the PRA, various related programs were set up to conduct different aspects of the analysis. Additionally, existing programs had tasks added to perform some analyses for the LaSalle PRA. The responsibility for overall direction of the PRA was assigned to the Risk Methods Integration and Evaluation Program (RMIEP). RMIEP was specifically responsible for all aspects of the Level I analysis (i.e., the core damage analysis). The Phenomenology and Risk Uncertainty Evaluation Program (PRUEP) was responsible for the Level II/III analysis (i.e., accident progression, source term, consequence analyses, and risk integration). Other programs provided support in various areas or performed some of the subanalyses. These programs include the Seismic Safety Margins Research Program (SSMRP) at Lawrence Livermore National Laboratory (LLNL), which performed the seismic analysis; the Integrated Dependent Failure Analysis Program, which developed methods and analyzed data for dependent failure modeling; the MELCOR Program, which modified the MELCOR code in response to the PRA's modeling needs; the Fire Research Program, which performed the fire analysis; the PRA Methods Development Program, which developed some of the new methods used in the PRA; and the Data Programs, which provided new and updated data for BWR plants similar to LaSalle. CECo provided plant design and operational information and reviewed many of the analysis results.

The LaSalle PRA was begun before the NUREG-1150 analysis and the LaSalle program has supplied the NUREG-1150 program with simplified location analysis methods for integrated analysis of external events, insights on possible subtle interactions that come from the very detailed system models used in the LaSalle PRA, core vulnerable sequence resolution methods, methods for handling and propagating statistical uncertainties in an integrated way through the entire analysis, and BWR thermal-hydraulic models which were adapted for the Peach Bottom and Grand Gulf analyses.

The Level I results of the LaSalle Unit 2 PRA are presented in: "Analysis of the LaSalle Unit 2 Nuclear Power Plant: Risk Methods Integration and Evaluation Program (RMIEP)," NUREG/CR-4832, SAND92-0537, ten volumes. The reports are organized as follows:

NUREG/CR-4832 - Volume 1:	Summary Report.
NUREG/CR-4832 - Volume 2:	Integrated Quantification and Uncertainty Analysis.
NUREG/CR-4832 - Volume 3:	Internal Events Accident Sequence Quantification.
NUREG/CR-4832 - Volume 4:	Initiating Events and Accident Sequence Delineation.
NUREG/CR-4832 - Volume 5:	Parameter Estimation Analysis and Human Reliability Screening Analysis.
NUREG/CR-4832 - Volume 6:	System Descriptions and Fault Tree Definition.
NUREG/CR-4832 - Volume 7:	External Event Scoping Quantification.
NUREG/CR-4832 - Volume 8:	Seismic Analysis.
NUREG/CR-4832 - Volume 9:	Internal Fire Analysis.
NUREG/CR-4832 - Volume 10:	Internal Flood Analysis.

The Level II/III results of the LaSalle Unit 2 PRA are presented in: "Integrated Risk Assessment For the LaSalle Unit 2 Nuclear Power Plant: Phenomenology and Risk Uncertainty Evaluation Program (PRUEP)," NUREG/CR-5305, SAND90-2765, 3 volumes. The reports are organized as follows:

NUREG/CR-5305 - Volume 1:	Main Report
NUREG/CR-5305 - Volume 2:	Appendices A-G
NUREG/CR-5305 - Volume 3:	MELCOR Code Calculations

Important associated reports have been issued by the RMIEP Methods Development Program in: NUREG/CR-4834, Recovery Actions in PRA for the Risk Methods Integration and Evaluation Program (RMIEP); NUREG/CR-4835, Comparison and Application of Quantitative Human Reliability Analysis Methods for the Risk

Methods Integration and Evaluation Program (RMIEP); NUREG/CR-4836, Approaches to Uncertainty Analysis in Probabilistic Risk Assessment; NUREG/CR-4838, Microcomputer Applications and Modifications to the Modular Fault Trees; and NUREG/CR-4840, Procedures for the External Event Core Damage Frequency Analysis for NUREG-1150.

Some of the computer codes, expert judgement elicitations, and other supporting information used in this analysis are documented in associated reports, including: NUREG/CR-4586, User's Guide for a Personal-Computer-Based Nuclear Power Plant Fire Data Base; NUREG/CR-4598, A User's Guide for the Top Event Matrix Analysis Code (TEMAC); NUREG/CR-5032, Modeling Time to Recovery and Initiating Event Frequency for Loss of Off-Site Power Incidents at Nuclear Power Plants; NUREG/CR-5088, Fire Risk Scoping Study: Investigation of Nuclear Power Plant Fire Risk, Including Previously Unaddressed Issues; NUREG/CR-5174, A Reference Manual for the Event Progression Analysis Code (EVNTRE); NUREG/CR-5253, PARTITION: A Program for Defining the Source Term/Consequence Analysis Interface in the NUREG-1150 Probabilistic Risk Assessments, User's Guide; NUREG/CR-5262, PRAMIS: Probabilistic Risk Assessment Model Integration System, User's Guide; NUREG/CR-5331, MELCOR Analysis for Accident Progression Issues; NUREG/CR-5346, Assessment of the XXSOR Codes; and NUREG/CR-5380, A User's Manual for the Postprocessing Program PSTEVNT. In addition the reader is directed to the NUREG-1150 technical support reports in NUREG/CR-4550 and 4551.

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1.0 INTRODUCTION

1.1 RMIEP

The Risk Methods Integration and Evaluation Program (RMIEP) was performed for the NRC by Sandia National Laboratories. The RMIEP program was the level I part of the Level III Probabilistic Risk Assessment (PRA) of the LaSalle County Station (LSCS). As part of this program, new methodologies were developed that would be applied in the LaSalle PRA. One task of the RMIEP program was defined as an external event scoping quantification study, which would select the external events to be included in the detailed external events analysis. NTS/Structural Mechanics Associates was retained by Sandia National Laboratories to perform the scoping quantification study for LSCS, which is reported elsewhere (Ravindra and Banon, 1992). As part of the LaSalle scoping quantification study, a review of existing methods and analytical techniques for probabilistic bounding analysis of potential external events at a nuclear power plant site was carried out. This report summarizes these methods and recommends the methods that could be applied in an external event scoping quantification as of the begining of 1985 when this task was completed.

Although a general external event scoping study would consider all possible external events at a site, seismic, internal flood, and fire events were excluded from the present study. Based on the experience gained from the recent PRA studies, they are considered to be potential contributors to plant risk and thus should be included in any detailed PRA external events analysis.

1.2 PRA Procedures Guide

A full-scope PRA of a nuclear power plant should consider all internal and external events that may pose a potential threat to the plant safety and contribute to the public risk. The detail to which the risk analysis is performed for each event depends on its frequency of occurrence and its effect on plant systems. In recent PRA studies, some external events (e.g., seismic, fire, internal flood, and extreme winds) have been treated in detail; other external events (e.g., turbine missiles, aircraft impact, and external flooding) have been dismissed as insignificant based on available data and judgment. Since PRA is a logical and formal procedure for examining all potential accidents, a logical and formal approach is needed for selection of important external events. The aim is to ensure that all potential external events are considered and that the significant ones are selected for more detailed studies. In fact, such a formal procedure has been developed in the PRA Procedures Guide, NUREG/CR-2300 (USNRC, 1983). Use of this procedure facilitates complete documentation of the basis for selecting the external hazards that deserve further detailed attention.

The PRA Procedures Guide gives appropriate methods for screening out external natural and man-made hazards from a full-scope PRA. Chapter 10 of the Procedures Guide gives the screening techniques based on the site location, design bases, and probabilistic bounding analyses. For those events considered to require detailed risk analysis, a general methodology is described. Chapter 11 of the Procedures Guide gives detailed procedures for performing risk analysis of seismic, fire, and flooding events. To date, early 1985, full-scope probabilistic risk assessments of seven nuclear power plants have been completed. These are Zion, Indian Point Units 2 and 3, Limerick, Seabrook, Midland, Millstone, and Oconee Unit 3. External events have been considered in each of these PRAs. Some form of scoping analysis has been followed in each case.

1.3 Objective

The objective of this report is to describe the scoping quantification methods for identifying external events (if any) that require an in-depth consideration in a PRA. The methods and events to be discussed supplement the seismic, flood, and fire events described in detail in the PRA Procedures Guide (USNRC, 1983) and are intermediate between initial screening methods and the detailed methods.

1.4 Report Outline

This report describes the methods for external event scoping quantification in a nuclear power plant PRA. It is divided into four chapters. Chapter 1 is an overview of the study and its relationship to RMIEP and the PRA Procedures Guide. Chapter 2 is a review of published external event PRA studies with the idea of identifying commonly used methods for external event scoping analysis. Chapter 3 describes the external event methodology as developed in the PRA Procedures Guide; it includes identification and initial screening of external events, approximate bounding analysis, and detailed risk analysis. In Chapter 4, bounding analyses are described for external events not analyzed in the PRA Procedures Guide: transportation accidents, extreme winds and tornadoes, aircraft impacts, turbine missiles, accidents in nearby industrial and military facilities, pipeline accidents, and chemical release. Chapter 5 gives a summary and salient conclusions of this report.

2.0 REVIEW OF PUBLISHED EXTERNAL EVENT PRA STUDIES

2.1 Introduction

To date, early 1985, seven full-scope probabilistic risk assessment studies have been published. They have included the consideration of external events to varying degrees of detail. Seismic, wind, flooding (internal), and fire have typically been treated extensively. Other external events have been considered; in many instances, some bounding analyses have been performed to demonstrate that the contributions of these events to plant risk are not significant. The methods used for each external event in these PRAs are essentially identical. In some instances, the analyst has stopped the evaluation of frequency at the occurrence of the hazard; in some instances, the analyst has found the need to carry the analysis up to the calculation of the core damage frequencies.

In the following sections, we briefly review these published external event PRA studies.

2.2 Zion

In the Zion Probabilistic Safety Study (CECO, 1981), the following external events were considered:

- Seismic
- Fire
- Flooding
- Tornadoes and Tornado Missiles
- Aircraft Accidents
- Transportation of Hazardous Materials
- Turbine Missiles.

Within the scope of the present report, we discuss the analyses performed for the last four external events listed above.

2.2.1 Tornadoes and Tornado Missiles

The annual probability of exceeding velocity V, P(V), at the site was calculated by (Garson, et al., 1974).

$$P(V) = \lambda (V_d/V)^{1/k} \bullet R'(V)$$

where λ = local mean rate of occurrence of tornadoes per square mile per year,

V_d = gale velocity,

k = 0.5 to 1.6; a parameter depending on a given storm; taken to be 1.6,

$$R'(V) = 17.4 * \exp(-0.014 * V) \text{ for } V \geq 290 \text{ mph.}$$

At Zion, if $\lambda = 1.0 \times 10^{-3}$, V_d = 40 mph and V = 360 mph, then

$P(V) = 2.8 \times 10^{-5}$ per year.

The 5 to 95 percent confidence bounds on P(V) were developed by considering the uncertainties in λ, k, and R'(V); these resulted in a bound for P(V) from 3.0×10^{-7} to 2.5×10^{-3}. The analysis was not carried further; it did not include the uncertainty in structural capacity and the consequences of structural failure in a tornado.

Based on the results of a tornado missile risk analysis performed by Twisdale, Dunn and Cho (1978), the probability of tornado missiles striking and scabbing the walls of Zion plant structures was estimated as 2×10^{-6} per year. The probability of damaging certain equipment thereby leading to core damage was estimated to be lower by a factor of 10^{-2} (i.e., 2×10^{-8} per year). This core damage probability was judged to be acceptably small, and the tornadoes and tornado missiles were not considered to be significant risk contributors.

2.2.2 Aircraft Accidents

The aircraft accident analysis considered the hazard from the operation of the Waukegan Memorial Airport, about 4 miles from the plant. Since the Zion plant structures have been designed to withstand an impact by aircraft under 30,000 pounds, the analysis was limited to large aircraft of the business jet category. The vulnerable plant area (A), which included containment buildings, the fuel handling building and the auxiliary building, was estimated as 0.006 mi^2 with 5 percent to 95 percent confidence bounds of 0.005 mi^2 to 0.008 mi^2, respectively. The aerial crash density (C) for the air carrier aircraft of 0.68×10^{-8} per operation was used. The annual probability of business jet aircraft impacting the plant was obtained as:

Mean	$= 2.0 \times 10^{-7}$
5 percent confidence bound	$= 1.5 \times 10^{-7}$
95 percent confidence bound	$= 5.0 \times 10^{-7}$

The annual probability of aircraft initiated core damage was estimated to be much less than 10^{-8} and was not considered to be a significant contributor to risk.

2.2.3 Transportation and Hazardous Materials

A review of the rail, highway, barge, and shipping traffic lanes in the vicinity of Zion revealed that potential accidents on them do not pose a threat to the plant safety. Similarly, no substantial concentrations of offsite or onsite hazardous materials exist near Zion. Hence, it was judged that no detailed probabilistic risk analysis of these external hazards was necessary.

2.2.4 Turbine Missiles

No detailed analysis of turbine missiles was done pending the resolution of the stress corrosion cracking issue in steam turbines. It was judged that the probability of turbine missile initiated core damage would be acceptably small.

2.3 Indian Point

The Probabilistic Safety Study (PSS) of Indian Point Units 2 and 3 (PASNY, 1982) analyzed the following external events:

Seismic
Fire
External and Internal Flooding
Winds and Tornado Missiles
Aircraft Accidents
Transportation and Storage of Hazardous Materials
Turbine Missiles

Within the scope of the present report, we will discuss the last four items in the above list.

2.3.1 Winds and Tornado Missiles

Indian Point Units 2 and 3 have some steel framed structures with metal siding and roofing that contain critical equipment. Also there are several exposed critical components (e.g., service water pumps, station auxiliary transformers, and gas turbines). These may all be subject to failure from wind and tornadic pressures or impact by tornado missiles. Therefore, a detailed analysis of the wind and tornado missiles was performed.

The analysis consisted of wind and tornado hazard analysis, wind fragility evaluation, and plant systems and accident sequence analysis. For details, the reader is referred to the Indian Point PSS report.

2.3.2 Aircraft Accidents

Aircraft crash probabilities as a result of operations from the Peekskill Seaplane Base and on the federal airways were evaluated using the methods outlined in the NRC Standard Review Plan (USNRC, 1975). By reviewing the plant arrangement, thicknesses of exterior walls and roofs of plant structures, and the systems needed for safe shutdown, it was determined that the probability of damage from aircraft impacts is very low.

2.3.3 Transportation and Storage of Hazardous Materials

Two aspects of the bounding analysis performed to evaluate the risks from transportation and storage of hazardous materials are worth noting here. An analysis of the possible accidental collision of barges of the Hudson River and its potential to cause a fire at the shoreline or a release of sodium hydroxide was conducted; the annual frequency of this event was estimated to be between 10^{-9} and 10^{-6} and hence would not contribute significantly to core damage frequency.

There are two natural gas transmission lines (26" and 30" diameter) passing through the site about 400 ft. from the nearest Unit 3 plant structure. The annual frequency of these pipes leaking and causing a fire hazard to the plant was estimated to be 5×10^{-7}. The probability of this event leading to core damage was judged to be extremely small.

2.3.4 Turbine Missiles

No detailed analysis of turbine missile induced risks was done pending the results of stress corrosion cracking studies being performed by the turbine vendor.

2.4 Limerick

In the Severe Accident Risk Assessment (SARA) of Limerick Generating Station (PECO, 1983), the following external events were studied:

Seismic
Fire
Flooding
Tornadoes
Transportation Accidents including Aircraft Impact
Turbine Missiles

2.4.1 Tornadoes

A bounding analysis of the risks from tornadoes was performed. Since Limerick is designed to current criteria for tornado loading and missile protection, the annual frequency of tornado-induced core damage is low, as expected. The analysis divided the tornadoes into two classes: less severe than the design basis tornado (DBT) and at or above DBT. Structures not specifically designed for DBT effects (e.g., electrical transformers and substations, turbine enclosure, condensate-storage tank, and cooling towers) are assumed to be severely damaged by wind speeds greater than 90 mph. Category I Structures specifically designed for DBT effects were assumed to fail in wind speeds greater than 300 mph. The annual frequency of tornadoes impacting the first class of structures with wind speeds in excess of 90 mph was estimated to be 2×10^{-5}. The DAPPLE index approach proposed by Abbey and Fujita (1975) and Abbey (1976) was utilized in this computation. Similarly, the annual frequency of tornadoes impacting the seismic Category I structures with wind speeds in excess of 300 mph was estimated at 10^{-7}. With these tornado-initiated accidents (i.e., damage to the structures), systems analysis were performed and concluded that the contribution of tornado-initiated accidents to the core damage frequency is negligible.

2.4.2 Transportation Accidents

The accidental release of toxic chemicals or flammable vapor clouds from the railroad, the highway, or the nearby Hooker Chemical plant was analyzed. It was concluded that such an accidental release would lead to a reactor accident only if the plant operators are affected in such a way that they cannot respond to an emergency if required to do so, or that they commit errors in responding to the emergency. The plant is equipped with systems to detect toxic vapors and to provide counter measures.

The plant requires about 20,000 lbs. of chlorine daily for water purification. Chlorine is shipped to the plant by railroad tank car. The accidental release of chlorine due to spontaneous failure, earthquake, shunting operations, and failure of pipework or couplings during discharge to the pumphouse was analyzed in detail. The annual frequency of core damage induced by chlorine release was estimated as 5×10^{-9}.

The Conrail railroad passes about 600 ft. from the nearest safety-related structure; this structure is designed to withstand the blast from 56 tons of TNT. Since the railroad carries a number of hazardous chemicals, such as propane, butadiene, and vinyl chloride in quantities larger than 56 tons of TNT, a bounding analysis of the explosion hazard was done. The frequency of overpressure due to accidents on the railroad exceeding the capacity of structures was estimated as the sum of the contributions from accident site explosions and drifting cloud explosions. The predicted frequency of this overpressure is 1.1×10^{-7} per year.

The bounding analyses performed for chlorine release and explosion hazards are the most detailed among the published PRAs.

2.5 Seabrook

The PRA study on the Seabrook Generating Station has considered many external events. Two basic approaches were used in analyzing the external events. One was a limited bounding analysis for some external hazards to show that the largest predicted sizes are not capable of causing significant damage to the plant or that the frequency of damage to plant components which may lead to core damage is extremely low when compared with other internal or external events. Wind and tornado events and turbine missiles are some examples of the events analyzed using this approach. The second approach consisted of a more detailed analysis for external hazards where it was unclear if the plant damage could be extensive or where the possible consequences could not be bounded. Examples of these events are seismic and fire.

There was no formal screening of external events for scoping quantification as described in the PRA Procedures Guide. However, even if such a screening technique were rigorously applied, it may not have uncovered any additional external events for quantification.

For each external initiating event, point estimates of plant damage state and core damage frequency were made. These values were compared to those obtained from internal event analysis to identify the initiators that are major contributors to each plant damage state.

2.5.1 Aircraft Crash Analysis

The frequency of aircraft accidents on the nearby air routes impacting the primary auxiliary building and control building was estimated as 3.4×10^{-7} per year. The method of analysis is very similar to that utilized in Oconee PRA (Section 2.8.2).

2.5.2 Hazardous Chemicals and Transportation Events

Three types of accidents were analyzed which have the potential to cause either: (1) hazardous concentrations of toxic or flammable gases or vapors inside the control room, (2) damage to safety-related structures through overpressure and missile impacts, or (3) the loss of offsite power without recovery. It was determined that the release of hazardous materials into the environment may be from large storage tanks in the area, a truck tanker passing by the plant, or from a nearby natural gas pipeline. Both explosions at the accident site and vapor cloud drift were considered. An analysis was done for the possibility of a truck running off the road and damaging offsite power transmission lines. These transmission lines are closely grouped near the plant switchyard, so a single accident damaging all the lines could result in a nonrecoverable loss of offsite power.

These analyses indicated that the mean frequency of hazardous chemicals entering the control room from its intake is less than 7×10^{-7} per year, and the frequency of a nonrecoverable loss of offsite power is 2.8×10^{-4} per year. The nonrecoverable loss of offsite power event was included in the plant damage state analysis.

The boundary analyses performed for tornado loading, and tornado and turbine missiles showed that their contributions to core damage frequency are very small.

2.6 Millstone Unit 3

The probabilistic safety study of Millstone Unit 3 (NUSCo, 1984) analyzed the following external events:

- Seismic
- Fire
- External and Internal Flooding
- Winds and Tornado Missiles
- Aircraft Accidents
- Transportation and Storage of Hazardous Materials
- Turbine Missiles

2.6.1 Winds and Tornado Missiles

The frequency of exceeding the design basis tornado windspeed of 360 mph at Millstone Unit 3 was calculated to be approximately 5.4×10^{-6} per year. The plant structures were assessed to withstand the design basis tornado loading with adequate margin. Hence, it was concluded that tornado loading would not contribute to the plant risk. Using the results of

Twisdale and Dunn (1981), the frequency of tornado missile-induced core damage accident sequence was estimated to be less than 1 x 10^{-6} per year.

2.6.2 Aircraft Accidents

Estimates of the frequency of aircraft-induced accidents at Millstone Unit 3 have been obtained as below:

General Aviation	- 1.5 x 10^{-6} per year
Commercial Aviation	- 1.2 x 10^{-7} per year
Military Aviation	- 3.4 x 10^{-9} per year

The plant vulnerability to light (general) aircraft crashes was examined. It was determined that a general aviation crash could initiate a loss of offsite power, but a core damage accident sequence would further require the independent random failure of onsite power. In view of the extremely low frequency associated with this scenario, (similarly with commercial and military aircraft crashes) it was concluded that aircraft hazards do not constitute a significant contributor to core damage.

2.6.3 Transportation and Storage of Hazardous Materials

The analysis included road, rail, and waterway traffic routes carrying hazardous materials. Also, onsite storage facilities were considered, as were nearby gas and oil pipelines. Based on the frequency of shipping, limited volumes of shipment, the strict controls placed on onsite traffic, and the distance from the transportation routes to the plant structures, it was concluded that the transportation and storage of hazardous materials do not contribute significantly to core damage.

2.6.4 Turbine Missiles

The analysis assumed the frequency of turbine failure as 10^{-4} per year. The resulting frequency of turbine missile damage to any one of the safety-related structure or equipment was found to be about 10^{-6} per year. Since there were several conservative assumptions made in the analysis, it was concluded that frequency of turbine missile induced core damage is well below 10^{-7} per year and consequently, turbine missiles do not significantly contribute to core damage.

2.7 Oconee

In the Oconee PRA (EPRI, 1984) external events were selected and analyzed essentially using the procedures described in the PRA Procedures Guide (USNRC, 1983). The events were treated on one of three levels:

1. Many hazards were eliminated from consideration because they are inapplicable to the Oconee site (e.g., avalanches, tsunamis, volcanic activity),

2. Bounding calculations were performed for some hazards to verify that their frequencies of occurrence were so low that they would not contribute importantly to core-damage frequency or risk, and

3. Detailed analyses were performed for events judged to be of more importance.

Table 2.7-1, reproduced from the Oconee PRA with permission, lists the external hazard and the level of detail employed in treating each of them. In the following, we summarize the approaches taken in performing the bounding calculations for tornado, aircraft impact, and turbine missiles.

2.7.1 Tornado

The tornado analysis considered the effects of wind loading and tornado missile impacts. A scoping analysis of the vulnerability of the plant to damage from tornado missiles was performed; it was judged that the accident sequences resulting from missile damage have negligible contribution to the core damage frequencies and hence were eliminated from further studies.

Based on an analysis of the vulnerability of structures and equipment at Oconee to tornado damage, it was judged that only tornadoes with windspeeds in excess of 150 mph can be damaging to the Oconee plant. The historical tornado data showed that in the period of 1950 to 1980, there have been 10 tornadoes with winds greater than 150 mph in the area within 50 nautical miles of the Oconee site. The mean damage length for these tornadoes was 10.6 miles and the mean damage width was 485′. The tornado damage origin area was calculated to be 1.1 square miles. The annual mean frequency of damaging tornadoes causing an initiating event was estimated to be 3.5×10^{-5}.

Figure 2.7-1, reproduced from the Oconee PRA with permission, shows the event tree describing the tornado-induced core-damage sequences. The important contributors are:

Core Damage Bin I: Early core damage at elevated pressure; leakage rates from the reactor coolant system corresponding to a small loss-of-coolant accident - total frequency 2.2×10^{-6}/year

Core Damage Bin III: Early core damage at elevated pressure, leakage rates corresponding to cycling pressurizer relief valves - total frequency 1.1×10^{-5} per year.

The total mean frequency of tornado-induced core damage sequences was estimated as 1.3×10^{-5} per year. This is small compared to the core damage frequencies of 8.8×10^{-5} per year by turbine-building floods and 2.5×10^{-4} per year from all internal and external events. In terms of the public risk, tornado induced accident sequences had smaller contribution compared to those induced by turbine-building floods and earthquakes.

2.7.2 Aircraft Impact

The Oconee Unit 3 is not near any major airports which have significant aircraft traffic in a weight category capable of damaging the plant. Therefore, plant risk caused by aircraft impact at the plant site was determined by air-corridor traffic in the vicinity of the plant.

The aircraft impact frequency was reported as

$$C = RA \bullet \Sigma\, N_i \bullet D_i$$

$$= RAN \bullet \Sigma\, f_i \bullet D_i$$

$$= RAND$$

where R = accident rate per aircraft mile,

A = target area (square miles) of site structures sensitive to aircraft impact,

N_i = average number of yearly flights on airway i,

D_i = density function describing the likelihood of aircraft impact on the ground as a function of the perpendicular distance from airway i (per mile),

f_i = fraction of flights on airway (i.e., $f_i = N_i/N$),

N = total number of yearly flights on airways within 20 miles of site, and

$D = \Sigma\, f_i \bullet D_i$.

The factors R, A, N_i and D_i were treated as probabilistic.

The aircraft-accident rate R was derived using the National Transportation Safety Board data on aircraft accidents for both U.S. air-carrier operations and U.S. general aviation. The accident rate for general aviation is about 50 times greater than that of air carriers. Less than 2 percent of general aviation aircraft have a gross take-off weight greater than 12,500 pounds, sufficient to cause serious damage to Oconee plant structures. Therefore, the air-carrier data was used to develop the aircraft-accident rate probability distribution, R, assuming it is representative of both air-carrier and general aviation traffic (of the relevant weight category). Based on a 20 year accident data for U.S. carriers, the aircraft accident rate, R, and its discrete probability distribution was derived (Table 2.7-2, reproduced from the Oconee PRA with permission). The median accident rate is 2.0×10^{-10} per aircraft-mile and the 5 to 95 percent confidence bounds are 7.6×10^{-11} to 5.1×10^{-10} per aircraft-mile.

The spatial accident density D_i was derived by examining the accident data on aircraft crash location relative to original flight path. This data was used to describe the prior distribution.

The posterior probability distribution on D_i was obtained using Bayes' Theorem. The median value of D_i was estimated as 0.019 per mile and the 5 to 95 percent confidence bounds were 0.012 to 0.029 per mile.

The target area of plant structures sensitive to aircraft impact, A, was estimated to have a median value of 0.01 square mile with 5 to 95 percent confidence bounds as 0.005 to 0.02 square mile.

The total number of yearly flights on airways within 20 miles of the site, N, was obtained by analyzing the IFR peak day traffic data for the 6-year period 1971 to 1977. The median of the peak day traffic is 261 flights per day and the standard deviation is 81 flights per day. The median of the average daily traffic was obtained by dividing the peak day traffic by 1.39 (this ratio of peak to average traffic is based on the statistics of the Federal Aviation Administration). The median and the standard deviation of the average daily traffic were calculated as 188 and 58 flights per day, respectively. The median yearly traffic was calculated as 68,600 and the 5 to 95 percent confidence bounds were 33,200 to 104,000.

The aircraft impact frequency was calculated using the probability distributions on R, D, A and N. The median impact frequency was found to be 2.5×10^{-9} per year and the 5 to 95 percent confidence bounds were 4.9×10^{-10} to 1.3×10^{-8} per year. Since this frequency was considered very low, the conditional probability of core damage given an aircraft impact on Oconee plant structures was not evaluated. The calculated impact frequency was used as a bounding estimate of the core damage frequency due to aircraft impact.

2.7.3 Turbine Missiles

A scoping analysis of turbine missile hazards at Oconee Unit 3 was performed using the missile characteristics provided by General Electric (1973). Based on the historical failure data, Patton, et al. (1983) have estimated that the rate of missile generating turbine failures is 1.64×10^{-4} per year, with 83 percent occurring at operating conditions and the remainder at overspeed conditions. Patton, et al, (1983) have also estimated that, on average, two disks fail in each turbine failure. Since there are 42 disks per low-pressure turbine at Oconee, the overall failure rate of 7.8×10^{-6} per year per disk was assumed.

Figure 2.7-2, reproduced from the Oconee PRA with permission, shows the critical areas of Oconee Unit 3 that are vulnerable to turbine missiles. The probability of one or more missiles striking a critical area was calculated using free-flight ballistics. Damage to safety-related equipment was assumed when the missile perforates the concrete external wall of the structure housing the equipment. The CEA-EDF perforation formula (Sliter, 1983) was used to estimate the probability of damage given a missile strike. Table 2.7-3, reproduced from the Oconee PRA with permission, gives a summary of estimated missile strike and damage rates for each critical area.

The frequency of core damage was estimated using the following system model. Core cooling can be achieved by means of the control room (B) or the auxiliary shutdown panel (A), and either of the penetration areas (D and E), along with equipment located in the auxiliary and turbine buildings. Alternatively, the core can be cooled with the standby shutdown facility (S) and the west penetration area (E). It is obvious that simultaneous failure of A, B and S, or D and E, or A, B and E will prevent core cooling. Therefore if we denote P_B, P_D etc., to describe the probability of damage to the control room, the east penetration area, etc., then the overall frequency of safety compromise (core damage) due to turbine missile damage is obtained as:

$$P \simeq P_A P_B P_S + P_D P_E + P_A P_B P_E$$

Using the missile damage rates given in Table 2.7-3, the frequency of core damage due to turbine missile was evaluated as 1.6×10^{-9} per year. This is extremely low compared to the core damage frequency caused by turbine-building flooding. Hence, turbine missiles were not considered in the Oconee PRA.

Table 2.7-1

Treatment of External Hazards in the Oconee PRA[a]

Hazard	Treatment
NATURAL HAZARDS	
Earthquake	Explicitly included
Flood--coastal	Not applicable
Flood--lake	Explicitly included
Flood--river	Explicitly included
Rainstorm	Explicitly included
Tornado	Explicitly included
Tsunami	Not applicable
Wind	Implicitly included under tornado
EXTERNAL MAN-MADE HAZARDS	
Aircraft-impact	Explicitly included
Industrial or military facility accident	Eliminated[b]
Pipeline accident	Eliminated[b]
Retaining-structure failure	Explicitly included
Surface vehicle explosion	Eliminated[b]
Surface vehicle impact	Eliminated

[a]External hazards from ANS 2.12 (1978).

[b]Review of the site vicinity indicated that there are no nearby hazardous facilities or routes used frequently to transport hazardous materials, and the frequency of these events was judged to be negligible for the purposes of this study.

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Table 2.7-2

Aircraft Accident Rate R

Accident rate[a] From	To	Discrete probability distribution	Cumulative probability[a]
0	6.5-11[b]	0.0381	0.0381
6.5-11	1-10	0.0804	0.1186
1-10	1.5-10	0.1692	0.2879
1.5-10	2.5-10	0.3170	0.6049
2.5-10	3.5-10	0.2113	0.8163
3.5-10	5.5-10	0.1578	0.9741
5.5-10	8-10	0.0257	0.9999

[a]Cumulative probability to the end of each interval.
[b]$6.5\text{-}11 = 6.5 \times 10^{-11}$.

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Table 2.7-3

Summary of Estimated Turbine Missile Strike and Damage Rates for Oconee Unit 3

Area	Strike rate (yr^{-1}) LTM	HTM	Total	Damage rate (yr^{-1}) LTM	HTM	Total
Auxiliary shutdown panel	5.6-7[b]	4.0-9	5.6-7	5.6-7	4.0-9	5.6-7
Control room	2.4-6	1.8-7	2.6-6	2.4-6[c]	1.1-8[c]	2.6-6
East penetration area	3.0-5	2.5-8	3.0-5	5.0-6	2.6-9	5.0-6
West penetration area	1.6-9	4.2-8	4.4-8	1.6-9[d]	4.4-9	6.0-9
Standby shutdown facility	(e)	1.8-7	1.8-7	(e)	1.9-8	1.9-8
Cableway	(e)	2.3-9	2.3-9	(e)	<1.0-9	<1.0-9
Spent-fuel storage	(e)	6.0-9	6.0-9	(e)	0	0
Borated-water storage tank	0	2.1-9	2.2-9	0	<1.0-9	<1.0-9
Steamline	0	2.2-8	2.2-8	0	2.2-8	2.2-8
Total			3.3-5			8.1-6

[a]Results based on a disk failure rate of 7.8×10^{-6} per year.
[b]Notation: 2.6-3 = 2.6×10^{-3}.
[c]Assumes all strikes are damaging strikes (either by perforation or by spallation).
[d]This is a safety-compromise rate, because the only path is through the east penetration area, its redundant component.
[e]These were not computed because penetration is negligible.

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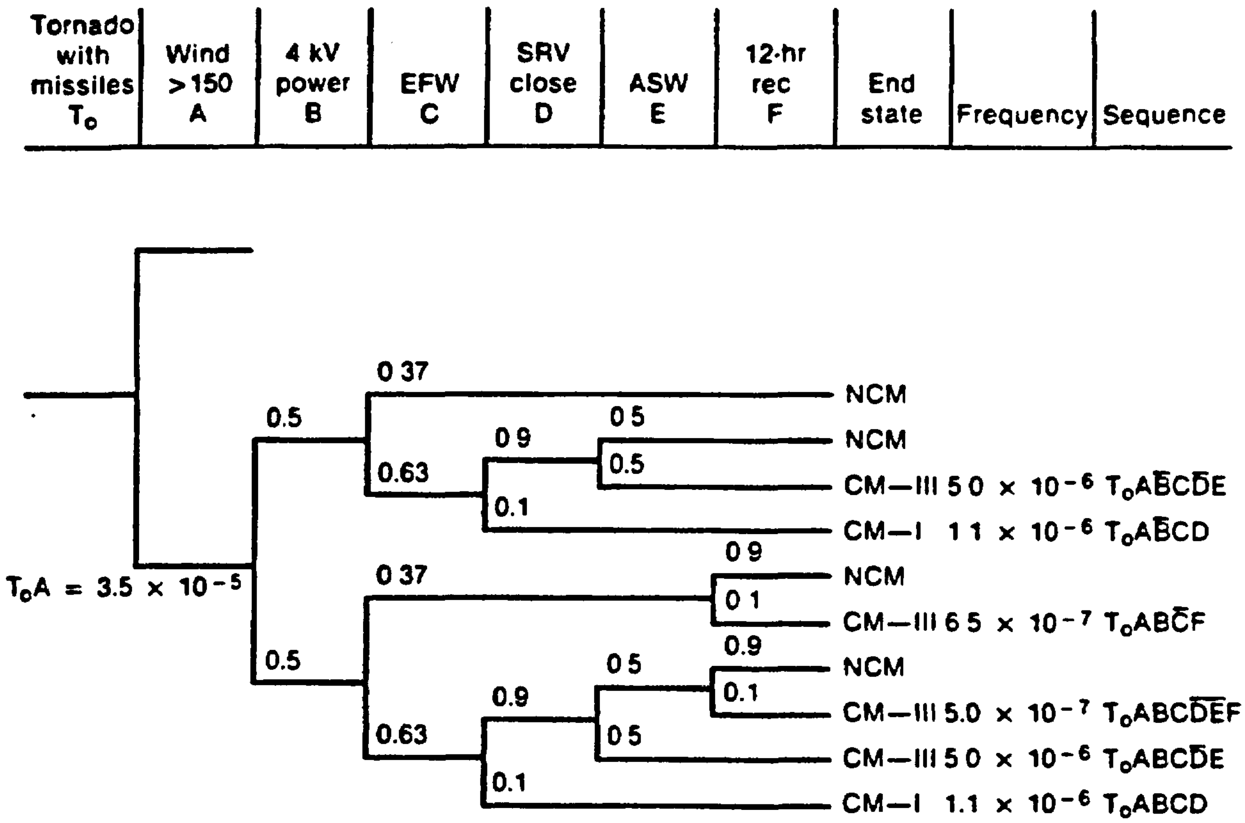

Event T A: Severe Tornado

Event B: 4 kV Power: Switchgear, 3TC, 3TD, 3TE, Main Feeder Bus

Event C: Emergency Feedwater

Event D: Safety Relief Valve Recloses

Event E: Auxiliary Service Water

Event F: Recovery of RCS Makeup within 12 hours

Figure 2.7-1. Event Tree for Sequences Initiated by a Severe Tornado

Reproduced from the Oconee PRA with permission.

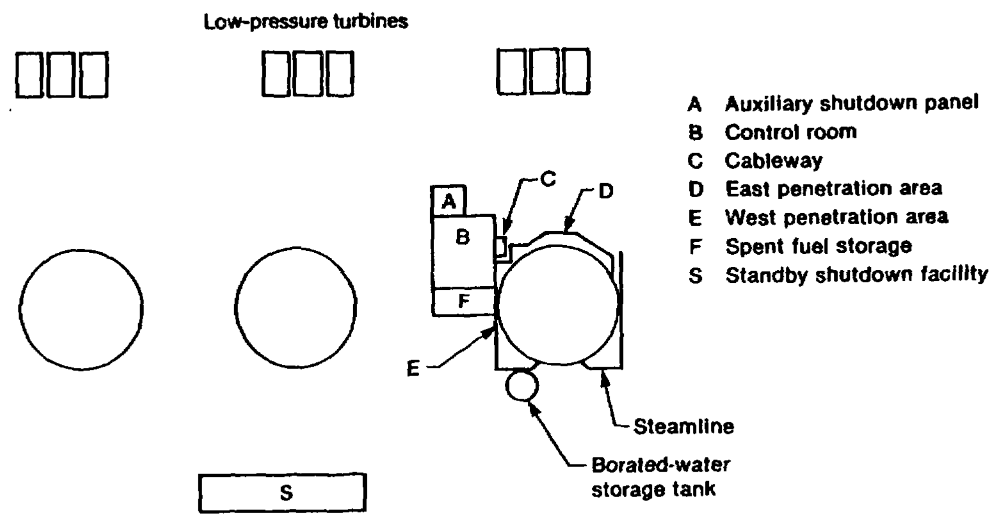

Figure 2.7-2. Oconee Unit 3 - Critical Areas for Turbine Missiles

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3.0 EXTERNAL EVENT METHODOLOGY

External event analysis in a PRA has three important goals:

1. The analysis should be complete in that all events are considered.

2. By following some selected screening criteria, the more significant events are identified for detailed analysis.

3. The selected events are analyzed in depth by taking into account the unique features of the events: hazard, fragility of structures and equipment, external-event initiated accident sequences, etc.

The first goal ensures that no significant events are overlooked. The second goal directs the allocation of limited resources to the study of significant events only. The third goal assures that differences between external events and internal events (i.e., common-cause and fragility-related failures) are recognized and explicitly treated. Based on the above goals, external event analysis may be considered as a three-stage process.

3.1 Identification and Initial Screening of External Events

In this stage, an extensive review of information on the site region and plant design is made to identify all external events to be considered. The data in the safety analysis report on the geologic, seismologic, hydrologic, and meteorological characteristics of the site region as well as present and projected industrial activities (i.e., the building of a reservoir, increases in the number of flights at an airport, construction of a road that carries explosive materials, etc.) in the vicinity of the plant are reviewed for this purpose. A visit to the plant site is useful in order to identify geographical and topographical features, to note any deviations to the information provided in FSAR and to assess the vulnerability of plant structures and systems to external events. In this way, a complete set of external events not limited either in size or intensity is generated. Table 3.1-1 reproduced from the PRA Procedures Guide (USNRC, 1983) is an example of such a list of external events.

In this stage, the external events identified as described above are screened in order to select the events for either approximate or detailed risk quantification. A set of screening criteria is formulated that should minimize the possibility of omitting significant risk contributors while reducing the amount of detailed analyses to manageable proportions. An example set of screening criteria given in the PRA Procedures Guide is as follows:

An external event is excluded if:

1. The event is of equal or lesser damage potential than the events for which the plant has been designed. This requires an evaluation of plant design bases in order to estimate the resistance of plant structures and systems to a particular external event. For example, it is shown by Kennedy, Blejwas, and Bennett (1983) that safety-related structures designed for earthquake and tornado loadings in Zone 1 can safely withstand a 3.0 psi static pressure from explosions. Hence, if the PRA analyst demonstrates that the overpressure resulting from explosions at a source (e.g., railroad, highway or industrial facility) cannot exceed 3 psi, these postulated explosions need not be considered.

2. The event has a significantly lower mean frequency of occurrence than other events with similar uncertainties and could not result in worse consequences than those events. For example, the PRA analyst may exclude an event whose mean frequency of occurrence is less than some small fraction of those for other events. In this case, the uncertainty in the frequency estimate for the excluded event is judged by the PRA analyst as not significantly influencing the total risk.

3. The event cannot occur close enough to the plant to affect it. This is also a function of the magnitude of the event. Examples of such events are landslides, volcanic eruptions and earthquake fault ruptures.

4. The event is included in the definition of another event. For example, storm surges and seiches are included in external flooding; the release of toxic gases from sources external to the plant is included in the effects of either pipeline accidents, industrial or military facility accidents, or transportation accidents.

In the PRA Procedures Guide (USNRC, 1983), the above screening criteria are applied to the external events identified in Table 3.1-1 in order to identify external events which may be deleted from further considerations. For any specific plant, the screening criteria should be formulated and applied to the external events using the particular characteristics of the plant and site region. By this process, a smaller set of external events is identified for risk assessment. For example, these could be in addition to seismic, fire, and internal flooding:

1. Aircraft impacts
2. External flooding
3. Extreme winds and tornadoes
4. Accidents in nearby industrial or military facilities
5. Pipeline accidents (natural gas, etc.)
6. Release of chemicals stored near the site
7. Transportation accidents
8. Turbine-generated missiles

Table 3.1-1

Natural and Man-Induced External Events to be Considered in PRA Studies[a]

Event	Applicable screening criterion[b]	Remarks
Aircraft impact	--	Site specific, requires detailed study
Avalanche	3	Can be excluded for most sites in the United States
Coastal erosion	4	Included in the effects of external flooding
Drought	1	Excluded under the assumption that there are multiple sources of ultimate heat sink or that the ultimate heat sink is not affected by drought (e.g., cooling tower with adequately sized basin)
External flooding	--	Site specific; requires detailed study
Extreme winds and tornadoes	--	Site specific; requires detailed study
Fire	--	Plant specific; requires detailed study
Fog	1	Could, however, increase the frequency of man-made hazard involving surface vehicles or aircraft; accident data include the effects of fog
Forest fire	1	Fire cannot propagate to the site because the site is cleared; plant design and fire-protection provisions are adequate to mitigate the effects
Frost	1	Snow and ice govern
Hail	1	Other missiles govern
High tide, high lake level, or high river stage	4	Included under external flooding

Table 3.1-1

Natural and Man-Induced External Events to be Considered in PRA Studies[a] (continued)

Event	Applicable screening criterion[b]	Remarks
High summer temperature	1	Ultimate heat sink is designed for at least 30 days of operation, taking into account evaporation, drift, seepage, and other water-loss mechanisms
Hurricane	4	Included under external flooding, wind forces are covered under extreme winds and tornadoes
Ice cover	1,4	Ice blockage of river included in flood; loss of cooling-water flow is considered in plant design
Industrial or military facility accident	--	Site specific; requires detailed study
Internal flooding	--	Plant specific; requires detailed study
Landslide	3	Can be excluded for most sites in the United States
Lightning	1	Considered in plant design
Low lake or river water level	1	Ultimate heat sink is designed for at least 30 days of operation, taking into account evaporation, drift, seepage, and other water-loss mechanisms
Low winter temperature	1	Thermal stresses and embrittlement are insignificant or covered by design codes and standards for plant design; generally, there is adequate warning of icing on the ultimate heat sink so that remedial action can be taken

Table 3.1-1

Natural and Man-Induced External Events to be Considered in PRA Studies[a] (continued)

Event	Applicable screening criterion[b]	Remarks
Meteorite	2	All sites have approximately the same frequency of occurrence
Pipeline accident (gas, etc.)	--	Site specific; requires detailed study
Intense precipitation	4	Included under external and internal flooding
Release of chemicals in onsite storage	--	Plant specific; requires detailed study
River diversion	1,4	Considered in the evaluation of the ultimate heat sink; should diversion become a hazard, adequate storage is provided
Sandstorm	1	Included under tornadoes and winds; potential blockage of air intakes with particulate matter is generally considered in plant design
Seiche	4	Included under external flooding
Seismic activity	--	Site specific; requires detailed study
Snow	1,4	Plant designed for higher loading; snow melt causing river flooding is included under external flooding
Soil shrink-swell consolidation	1	Site-suitability evaluation and site development for the plant are designed to preclude the effects of this hazard
Storm surge	4	Included under external flooding
Transportation accidents	--	Site specific; require detailed study

Table 3.1-1

Natural and Man-Induced External Events to be Considered in PRA Studies[a] (concluded)

Event	Applicable screening criterion[b]	Remarks
Tsunami	4	Included under external flooding and seismic events
Toxic gas	4	Site specific; requires detailed study
Turbine-generated missile	--	Plant specific; requires detailed study
Volcanic activity	3	Can be excluded for most sites in the United States
Waves	4	Included under external flooding

[a]Modified from ANSI/ANS-2.12-1978 (American Nuclear Society, 1978).

[b]See Section 10.3.3 for a sample set of screening criteria. The values given in this table are intended for illustration purposes only. For a specific PRA project, the analyst of external events should establish site-specific screening criteria and apply them to select the external events that may require a detailed study.

Reproduced from PRA Procedures Guide, USNRC, 1983.

3.2 Approximate Bounding Analysis of Risks from External Events

Although a specific external event is identified for further risk analysis, it may still be possible through simplified analysis to show that the event is not significant. This is an essential step in the external event PRA as it minimizes the amount of analyses required.

The key elements of the analysis of risk from an external event are:

1. Hazard analysis
2. Plant-system and structure response analysis
3. Evaluation of the fragility and vulnerability of plant structures and equipment
4. Plant system and accident sequence analysis
5. Consequence analysis

3.2.1 Hazard Analysis

A hazard analysis estimates the frequency of occurrence of different intensities of an external event. These are called "hazard intensities." Typically, the output of a hazard analysis is a hazard curve giving exceedance frequency versus hazard intensity. Since there is normally a great deal of uncertainty in the parameter values and in the mathematical model of the hazard, the effects of uncertainty are often represented through a family of hazard curves with a probability distribution assigned to the family of curves, representing the relative likelihood of one hazard curve relative to the others.

3.2.2 Response and Fragility Evaluation

The analysis of plant system and structure response translates the hazard input into responses of structures, piping systems, and equipment. The fragility or vulnerability of a structure or equipment is the conditional frequency of failure given a value of the response parameter. In some external event analyses, the response and fragility evaluation are combined and the fragility is expressed in terms of a global parameter of the hazard (e.g., tornado wind speed).

3.2.3 Accident Sequence and Consequence Analysis

The analysis of plant systems and accident sequences consists of developing event trees and fault tress in which the initiating event can be the external hazard itself or a transient or LOCA initiating event induced by the external event. Various failure sequences that lead to core damage, containment failure, and a specific release category are identified and their conditional frequencies of occurrence are calculated. The unconditional frequency of core damage or of radionuclide release for a given release category is obtained by integrating over the entire range of hazard intensities. If the consequence analysis is carried out separately for each external event, the output could be curves of frequencies of damage (i.e., early fatalities, latent-cancer deaths, or property damage).

3.2.4 Approximate Analysis of Risks

In this stage of the analysis, an external event can be excluded from further risk assessment based on the frequency of core damage (or serious release) induced by the event. Calculation of this core damage frequency may be done using different bounding assumptions as explained by the following example. Typically, nuclear power plants are sited such that the accidental impact of plant structures by aircraft is highly unlikely. For the purposes of an external event PRA, the risk from aircraft accidents may be assessed at different levels. The mean annual frequency of aircraft impacting the plant during takeoff, landing, or in flight may be determined. If this hazard frequency is very low (e.g., 10^{-7} per year), then the aircraft impact as an external event may be eliminated from further study. This approach assumes that the aircraft impact results in damage of the structure leading to core damage or serious release (this assumption is likely to be highly conservative). If the frequency of aircraft impacting the plant structures is estimated to be larger, the fragility of the structures may be evaluated to make a refined estimate of the frequency of core damage. Further refinements could include (1) elimination of certain structural failures not resulting in core damage (e.g., damage to diesel generator building may not result in core damage if offsite electrical power is available); and (2) performing a plant-systems and accident analysis to calculate the core damage frequency. This example shows that for some external events, it may be sufficient to perform only the hazard analysis; for some others, the hazard analysis and a simple fragility evaluation may be needed; in rare cases, a plant-systems and accident sequence analysis may be necessary.

The procedure of screening out the external events in this stage consists of (1) establishing an acceptably low mean frequency of core damage based upon simplifying conservative assumptions (e.g., 10^{-7} per year); (2) performing bounding calculations of the mean core damage frequency for each external event and (3) eliminating from further consideration those events which have mean core damage frequencies less than the acceptable value (i.e., 10^{-7} per year).

As part of the plant licensing evaluation, probabilistic analyses are performed for a few external events and the frequencies of unacceptable damage (i.e., exceedence of 10 CFR Part 100 guideline exposures) caused by these external events are shown to be very small. The information contained in the plant safety analysis reports and the analyses performed at the design stage in support of FSAR should be reviewed in an external event PRA and any new information gathered as part of PRA effort should be used in performing the bounding analyses. Since the PRA attempts a realistic risk evaluation, the conservative bias introduced by the assumptions made in the licensing analysis should be appropriately removed.

3.2.5 Treatment of Uncertainty

Uncertainties exist in the hazard analysis and the fragility evaluation of plant structures and equipment. These arise from lack of data and in the use of analytical models to predict failure. The uncertainty in each phase of the external event PRA is to be estimated using limited analysis, available empirical data and expert judgment. Typically, the uncertainties in hazards and fragilities are represented by families of hazard and fragility curves. The uncertainties in different phases of the external event PRA are propagated using the methods described in Chapter 10 of the PRA Procedures Guide.

3.3 Detailed Analysis of Risks From External Events

For the external events that are not screened out in the first two stages, a detailed risk analysis is necessary. Presently, such an analysis is usually done for seismic events, internal flooding, and fire. The risk analysis methods are described in Chapter 11 of the PRA Procedures Guide. Detailed PRA analysis for other external events is outside the scope of the present document.

4.0 BOUNDING ANALYSES FOR SELECTED EXTERNAL EVENTS

Methods of bounding analysis for a selected number of external events are described in this chapter. The external events which are included in this chapter are judged to be potentially more significant risk contributors than other external events. These events include transportation accidents, extreme winds and tornadoes, aircraft impact, and turbine missiles. Detailed analyses of seismic, fire, and flooding events are done in the PRAs and, as such, they are not included in this report. For the methodology to perform detailed analysis of any external event, the reader is referred to Chapter 10 of the PRA Procedures Guide (USNRC, 1983) or to the appropriate RMIEP report listed in the Foreword. For each external event, collection of information, FSAR analysis, and method of bounding analysis is presented. The bounding analyses methods which are presented in this chapter are those which are used in the LaSalle external event scoping quantification (Ravindra and Banon, 1992). These methods are deemed to be appropriate, but they are not the only methods which could be used for this purpose, i.e., other probabilistic models may be used for bounding analyses if they include the same features as the models that are presented in this chapter.

4.1 Transportation Accidents

4.1.1 Collection of Information

There are three typical modes of transportation near nuclear power plants; namely, highway, railroad, and river. Information regarding these modes of transportation is usually available in a plant FSAR in the form of type and number of shipments of hazardous materials on the transportation routes in the vicinity of the plant, maximum quantity of material in any shipment, and location of the routes with reference to plant structures. Other information which may be required for a probabilistic bounding analysis would include accident rates for barges, railroads, and highways. Statistics of accident rates for railroads, highways and barges have been used in previous external event PRAs (e.g., Severe Accident Risk Assessment, Limerick Generating Station, PECO, 1983).

4.1.2 FSAR Analysis

A transportation accident near a plant could lead to core damage in one of the following ways: (1) a chemical explosion due to a transportation accident may cause damage to Category I structures and safety-related equipment, and (2) toxic chemicals which are spilled in a transportation accident may drift into the control room and cause incapacitation of the operators. Both of these accident modes have been mentioned in the USNRC Regulatory Guides as will be discussed below.

A review of the plant FSAR should be conducted to determine if the hazards from transportation and storage of chemicals were considered in the plant design and if the plant design meets the regulatory requirements in this regard. In this review, any changes in the transportation characteristics (i.e., quantity and type of hazardous material, routes) and storage of chemicals should be examined to determine their effect on the FSAR conclusions.

A chemical explosion near the plant structures may cause overpressure, dynamic pressures, blast-induced ground motion, or blast generated missiles. However from previous research in this area, it has been determined that overpressures would be the controlling consideration for explosions resulting from transportation accidents (Regulatory Guide 1.91). An accidental overpressure at the site can also occur because of vapor cloud explosions drifting towards the structures. This type of explosion involves complex phenomena which depend on the material involved, combustion process, and topographical and meteorological conditions. According to a study by Eichler and Napadensky (1978), present theoretical and empirical knowledge is too limited to quantitatively evaluate realistic accidental vapor cloud explosion scenarios. However, vapor cloud explosions are implicitly included in the TNT equivalents that are used to represent transportation accidents.

According to the Regulatory Guide 1.91, chemical explosions which would result in free-field overpressures of less than 1 psi at the site do not need to be considered in the plant design. Based on experimental data on hemispherical charges of TNT, a 1 psi pressure would be translated into a safe distance R (feet), which is defined as:

$$R \geq KW^{1/3} \qquad (4.1\text{-}1)$$

where K = 45 and W is an equivalent weight of TNT charges. The maximum probable equivalent TNT charge is 50,000 lbs for a highway truck, 132,000 lbs for a single railroad boxcar, and 5,000 tons for a river barge. Figure 4.1-1, which is reproduced from Regulatory Guide 1.91, shows the safe distances for a highway truck, a railroad boxcar, and a river barge.

Although the NRC Regulatory Guide is conservative in defining the equivalent TNT explosive loads, it is nonconservative with respect to structural capacities because of the following reason. The free-field pressure wave which results from a TNT explosion is reproduced from Kennedy, et al. (1983) in Figure 4.1-2. This pressure consists of an instantaneous rise and a decay to zero followed by a slight negative pressure. The values of peak incident overpressure (P_{so}), positive phase impulse, I, and positive duration (t_d) for values of ground range $\lambda = R/W^{1/3}$ are shown in Figure 4.1-3, also reproduced from Kennedy. The curves in this figure are based on field blast experiments. Note from Figure 4.1-2 that the overpressure acting on the wall panels of a structure also includes a reflected pressure. Therefore, the overpressure on the wall panels is approximately twice the incident overpressure. In addition, the dynamic effect of peak overpressure for a wall panel may be significant. Figure 4.1-4 shows dynamic load factors for a single-degree-of-freedom system as a function of the ratio of pulse duration (t_d) to the period of the structure (T) for a triangular pulse and a rectangular pulse (reproduced from Biggs, 1964 with permission). It can be observed that the dynamic load factor for a pulse can reach a maximum value of 2.0 for higher t_d/T ratios. As a result of pressure reflection and dynamic effects, a free-field overpressure of 1 psi at the site could result in an effective static overpressure of up to 4 psi on the wall panels. Therefore, a more detailed study of overpressure due to transportation explosions may become necessary. If the FSAR considered the hazard from transportation and storage of chemicals, if there are no changes in the operations as regards transportation and storage, and if the above nonconservatism can be shown to be unimportant, then no further analysis of the hazards is deemed necessary.

A toxic chemical spill near a power plant would pose a danger to the plant if the chemicals penetrate into the control room air intakes and cause incapacitation of the operators. Regulatory Guide 1.78 discusses the assumptions for evaluating the habitability of a nuclear power plant control room during a postulated hazardous chemical release. In this approach, toxicities of hazardous chemicals potentially involved in accidental releases are identified. Then, based on each toxicity limit, a safe distance is calculated for different amounts of the hazardous chemicals. It should be noted that the safe distance in this case does depend on the leaktightness of plant control rooms, i.e., more hazardous chemicals are allowed near a control room which has low leakage construction features. A probabilistic bounding analysis of the plant for toxic chemical accidents is required only if chemicals are stored closer than the calculated safe distances.

4.1.3 Bounding Analysis

Section 4.1.2 described the methods that could be used to screen transportation accidents based on FSAR information. In this section, methods of bounding analysis for screening transportation accidents will be discussed. It is suggested that these accidents may be screened initially without resort to probabilistic models. However, more detailed probabilistic models would be required if the accident effects are judged to be important. For the purpose of bounding analysis, explosions and toxic chemical releases are considered separately. Toxic chemical release is discussed in Section 4.5.3.

As explained in Section 4.2, nuclear power plants depending on their location are designed for different magnitude tornadoes. One of the tornado effects against which plants are designed is a uniform pressure drop due to passage of a tornado field. As an example, for Zone I tornadoes, plants are designed for a pressure drop of 3.0 psi. If maximum overpressure due to a transportation accident including the effects of reflective pressure and dynamics is less than the tornado design pressure, then the probability of core damage due to transportation accidents is expected to be negligible. It is noted that such an analysis should consider each accident at the closest possible point to the plant structures. Therefore, the method of analysis would be as follows. Given an accident (e.g., truck, barge, or railroad), maximum equivalent TNT weights of chemicals can be based on the NRC recommendations (Reg. Guide 1.91). These equivalent TNT weights are 50,000 lbs for truck loads, 132,000 lbs for railroad boxcar loads, and 5,000 tons for river vessel loads. Although vapor clouds are not specifically considered in such an analysis, these effects are implicitly taken into account in defining the equivalent TNT loads. In the study by Eichler, Napadensky, and Mavec (1978), the hazard from vapor cloud drifts which could be generated in barge accidents were examined. According to this study, although a vapor cloud may theoretically drift towards the site and produce higher incident overpressures at the site, the following reasons minimize the threat due to drifting vapor clouds.

- Probability of a vapor cloud explosion rapidly decreases due to the decrease in concentration as it travels away from the accident site.

- Range of unfavorable wind directions (i.e., wind directions that can impact the plant) rapidly decreases as spill to site distance increases.

Based on this study, it was concluded that the equivalent TNT explosive weights which are specified by the NRC are very conservative. Next, Figure 4.1-3 can be used to calculate the maximum incident overpressure P_{so} for the accident. If 4 x P_{so} is lower than the design tornado overpressure for the plant, then transportation accidents may be ignored. However, if this condition is not met, one may take advantage of expected inelastic energy absorption capacity of reinforced concrete wall panels. According to Kennedy et al. (1983), a conservative ductility value equal to 3.0 may be used for reinforced wall panels. Also, in the study by Kennedy et al. (1983), conservatism factors which could be expected due to inelastic energy absorption have been presented, e.g., it has been shown that there is at least a conservatism factor in the range of 2.0 to 3.0 due to panel ductilities. If the median capacity of wall panels including the ductility factor is higher than the maximum overpressure which can be expected at the site, transportation accidents could be eliminated from further consideration. Otherwise, a simple probabilistic bounding analysis may be performed which is discussed in the following paragraph.

From Figure 4.1-3 and knowledge of transportation routes near the plant, one can determine the segment of each transportation route which is most critical in terms of potential overpressures at the site. For example, this segment can be determined by identifying the two points on a route where accidents could cause overpressures equal to the wall panel capacities. From accident rate data per length of each transportation mode, one can then determine the frequency of an accident resulting in unacceptable overpressures for each route. If the sum of these accident frequencies does not exceed a predetermined limit (e.g., 10^{-7} per year), transportation accidents near the plant can be eliminated from further consideration.

In this section, we have described how approximate analysis using the Regulatory Guide criteria may be performed to assess the contribution of transportation accidents to the frequency of core damage. If this contribution is judged to be unacceptable, a detailed analysis of the risks from the transportation and storage of chemicals may be conducted. For a detailed treatment of this issue, the reader is referred to the Limerick Severe Accidents Risk Assessment (PECO, 1983) report.

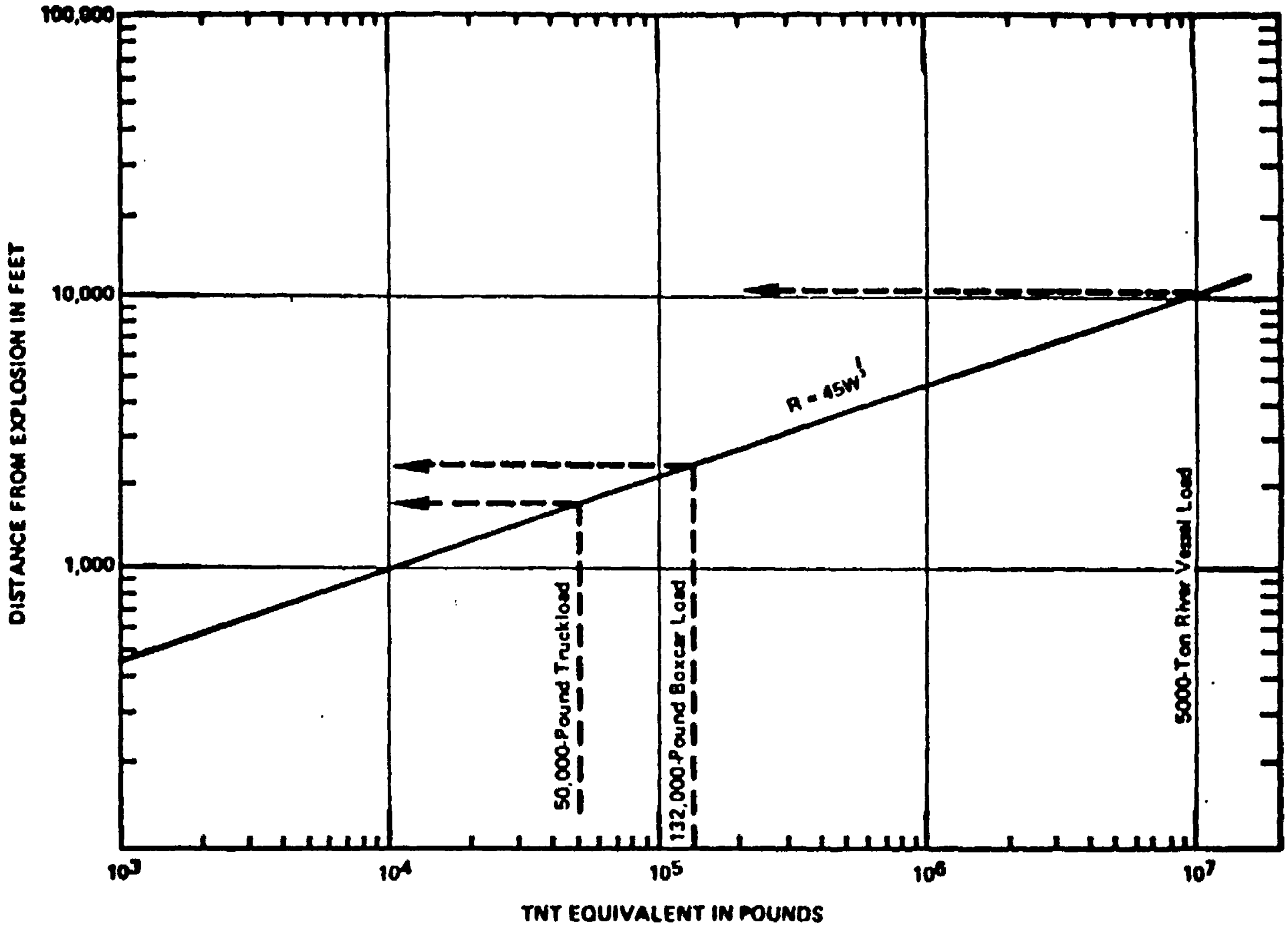


Figure 4.1-1. Radius to Peak Incident Pressure of 1 PSI

Reproduced from Regulatory Guide 1.91.

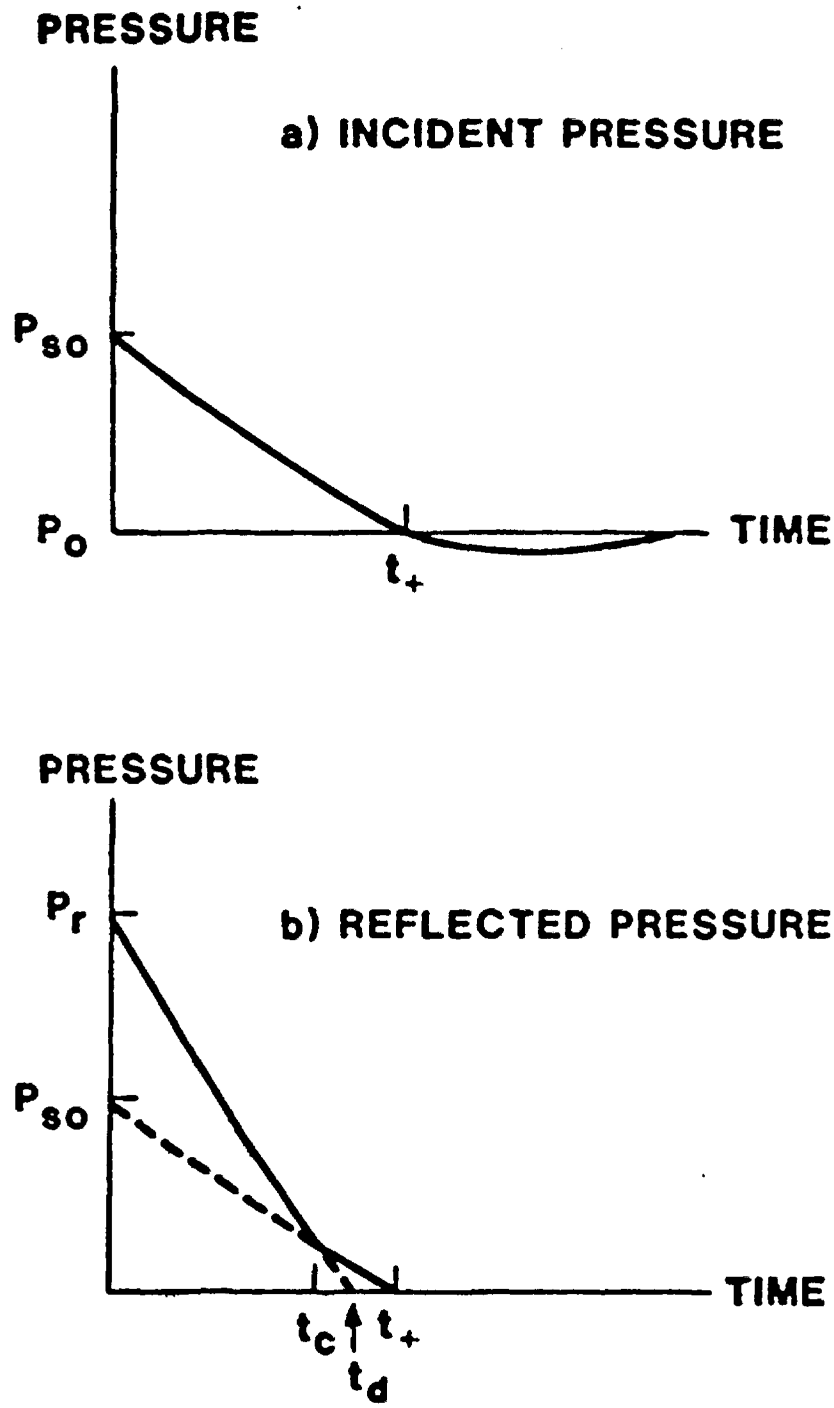


Figure 4.1-2. Pressure Pulses from TNT

Reproduced from Kennedy, 1983.

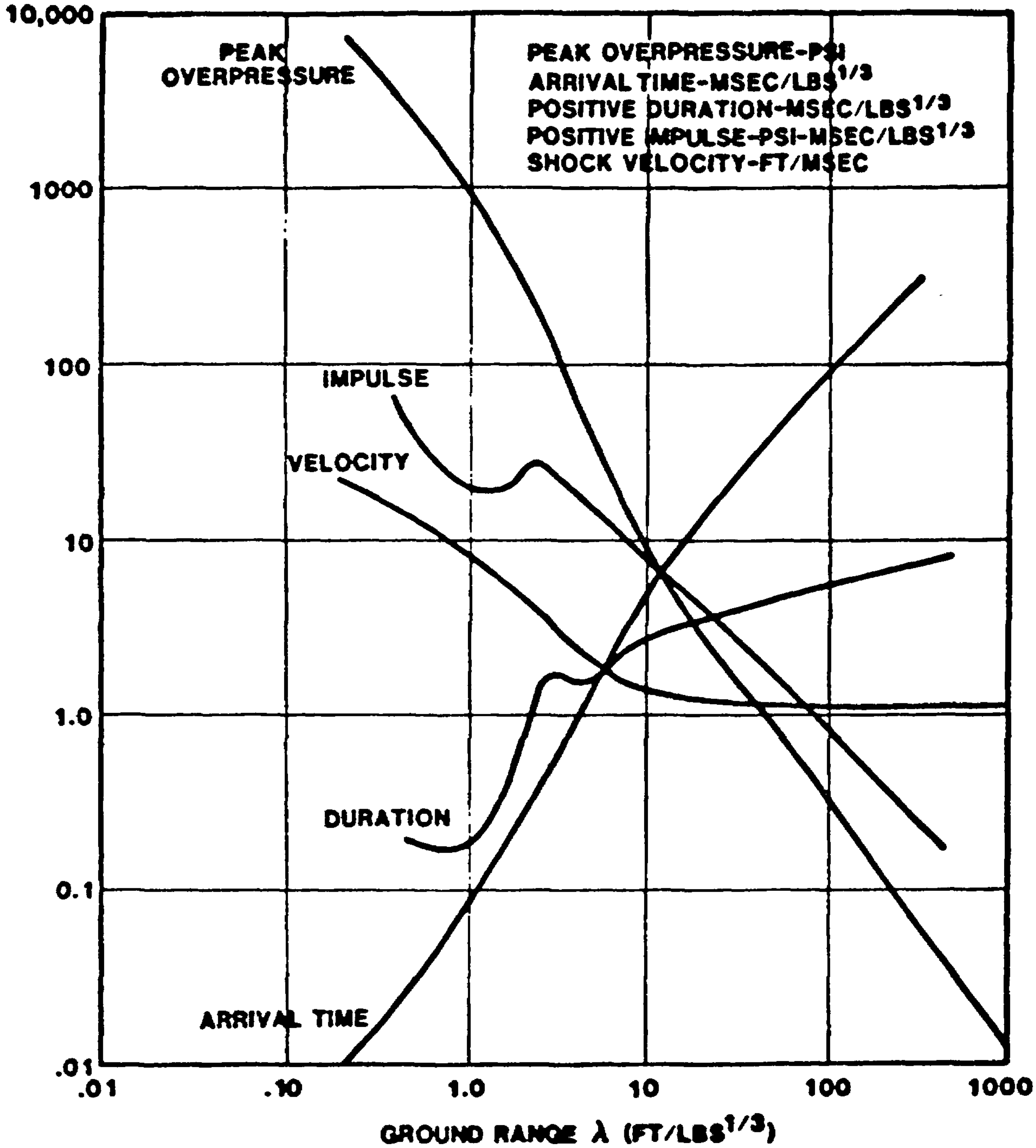


Figure 4.1-3. Free-Field Blast Wave Parameters Versus Scaled Distance for TNT Surface Bursts (Hemispherical Charges)

Reproduced from Kennedy, 1983.

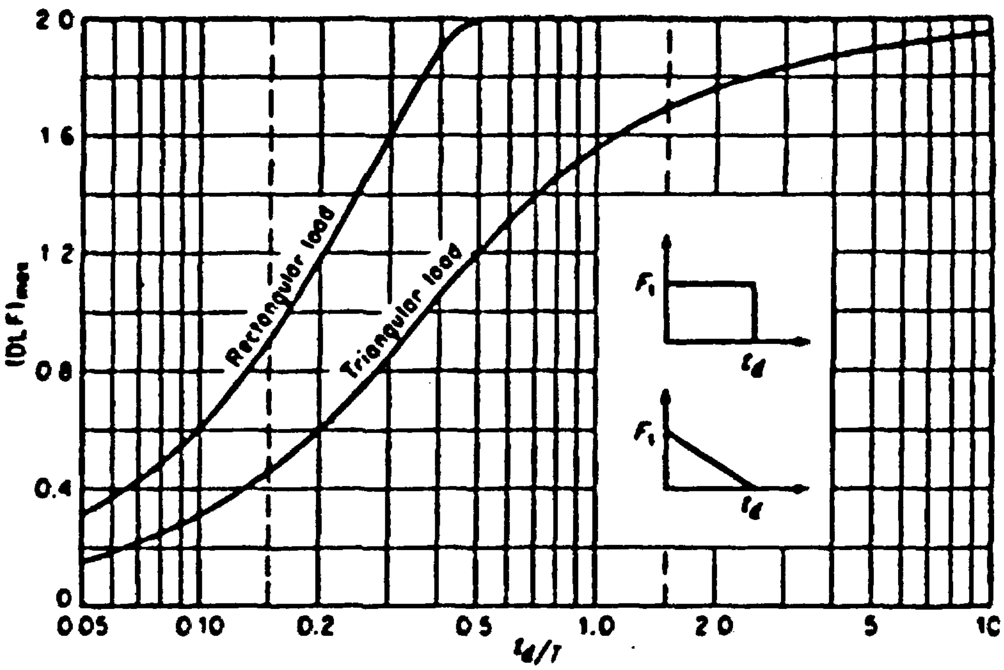


Figure 4.1-4. Dynamic Load Factors. Maximum response of one-degree elastic systems (undamped) subjected to rectangular and triangular load pulses having zero rise time.

Reproduced from Biggs, 1964 with permission.

4.2 Extreme Winds and Tornadoes

4.2.1 Collection of Information

In order to perform a probabilistic bounding analysis for winds and tornadoes, information regarding the plant design should be collected. One source is the final safety analysis report (FSAR). Other details regarding structural dimensions and wall thicknesses may be obtained from plant drawings. For structures which are enclosed by metal siding, data may be obtained from the metal siding manufacturer. In general, one would be able to obtain test data and analytical results for the siding behavior under applied pressure loads. Since nuclear power plants are generally designed to resist lateral seismic loads, nuclear power plant structures are expected to have a high capacity against wind and tornado loads. The governing mode of failure for winds and tornadoes as well as for tornado generated missiles is failure of exterior walls or metal sidings. Therefore, one needs to concentrate only on the exterior walls of plant structures, i.e., failure of metal siding or out of plane failure of wall panels under wind and tornado pressure loads. For tornado-generated missiles, impact formulas have been developed based on test results which could be used to evaluate the fragility of wall panels for different missile sizes and weights.

Other data which are required for a wind and tornado bounding analysis include records of maximum yearly wind speeds at the site and the number of occurrences of tornadoes in the vicinity of the plant site. If maximum yearly wind speeds are not available for a site, data from nearby weather stations may be used. Also, frequencies of occurrences of tornadoes at various regions in the United States have been developed in terms of tornado zones which could be used in lieu of historical local information.

4.2.2 FSAR Analysis

The design basis wind, the design basis tornado, and the spectrum of tornado generated missiles which are used in a plant design are indicated in the Final Safety Analysis Report. Generally, both seismic Category I structures and non-Category I structures are designed for wind loads. However, the design basis wind loads may be different for these two classes for structures, i.e., seismic Category I structures are usually designed for higher wind loads. Also, seismic Category I structures are required to be designed against the effects of tornadoes and tornado generated missiles whereas other nuclear power plant structures are not usually designed against tornado loads and missiles.

Wind and tornado analyses, presented in the FSAR, are usually not directly applicable in a probabilistic bounding analysis. This is because FSAR analyses are performed from the standpoint of plant design and conformance with the regulatory requirements. Therefore, risk due to winds and tornadoes is not usually calculated in a FSAR analysis. However, a plant FSAR would indicate the information such as locations of safety-related equipment, details of outside walls, and properties of metal sidings which are required for a probabilistic analysis. Other information regarding walls and sidings can be found in the plant engineering drawings.

As mentioned above, seismic Category I structures in a nuclear power plant are required to be designed against tornado load effects. The design tornado loads include the tornado rotational speed, translational speed, and a rapid pressure drop.

Two different regionalization schemes are currently used for tornadoes. Figure 4.2-1 shows the regionalization scheme which was proposed by WASH-1300 (Markee et al., 1974) and Figure 4.2-2 shows the regionalization scheme proposed by Twisdale and Dunn (1981). Regulatory Guide 1.76 (USNRC) describes the design basis tornado for nuclear power plants. Regulatory Guide 1.76 (USNRC) has adopted the regionalization scheme in WASH-1300. Table 4.2-1, which is reproduced from Regulatory Guide 1.76, lists the design tornado characteristics for each region. If a structure has been designed against tornado loads, the straight extreme winds will not govern in its design, i.e., the annual frequency of exceedence of 240 mph (which is the lowest tornadic wind speed) straight winds is negligibly low. Therefore, for the buildings having tornado design, it is sufficient to consider only tornadoes in a probabilistic bounding analysis. Since safety-related components in modern plants are all located in seismic Category I structures, a probabilistic bounding analysis for modern plants should concentrate on the risk from failure of Category I structures due to tornado winds. On the other hand, for older plants it is possible to find some safety-related components outdoors or in non-Category I structures. In such cases, the non-Category I structure may have a wind capacity much lower than 240 mph winds. For example, if a building has a wind capacity of 120 mph, the frequency of exceedence of 120 mph straight winds is much higher than the frequency of a tornado strike at the plant. This is true because tornadoes are rare events. Thus, for non-Category I structures containing safety-related equipment, both straight winds and tornadoes must be taken into account.

The probabilistic bounding analysis methodology described in the next section is for tornado risks. For the straight winds, development of site hazard is briefly described as follows. Maximum yearly wind speeds at the site or at a weather station near the site can be used to find the probability distribution of maximum annual wind speeds (Changery, 1982). Usually, an extreme value Type I distribution is fit to the data. Therefore, a hazard curve for maximum annual straight winds can be developed for the plant site. Once the wind hazard curve is developed, evaluation of fragilities and accident sequences would be similar to those for tornado loads.

4.2.3 Bounding Analysis

Characteristics of Tornadoes - Tornadoes are rare events which are usually characterized by their rate of occurrence, direction, maximum intensity, path length, and path width. The most important aspect of a tornado is its maximum wind speed. Other characteristics of a tornado such as velocity, pressure, and pressure drop can be predicted from maximum tornado wind speeds. The methodology for a tornado bounding analysis is described in Reinhold and Ellingwood (1982). In this approach, the tornado hazard curves at the site are developed in terms of maximum tornado wind speeds, i.e., the hazard curve is a plot of annual frequency of exceedence for a range of maximum tornado wind speeds. It can be shown that such tornado hazard curves are dependent on the geometry of structures exposed to tornadoes.

Tornadoes are usually classified according to their intensity. The most common classification of tornadoes is the Fujita F-Scale and Pearson length and width scale (FPP) which is a measure of destructiveness of a tornado (Fujita and Pearson, 1973). In this scale, tornadoes are assigned a number from 0 to 6 (F0 - F6) with higher numbers indicating higher intensity tornadoes. Table 4.2-2, reproduced from Fujita with permission, shows the FPP classification of tornadoes along with intensity scale, length scale, and width scale. Also, listed in Table 4.2-2 is an area intensity scale which is based on total damage area. The F-scale intensities are assigned using a qualitative assessment of the worst damage that occurs during a tornado. This is usually accomplished by observing the damage to residential buildings or other structures and calculating the pressure that is needed to cause the observed damage. From calculated tornado wind pressure, one can find the maximum velocity that could generate such pressures. Since classification of tornadoes is based on observation of damage rather than direct measurement of wind speed, two types of errors can be introduced in this process.

Direct classification errors are due to inaccuracies in assigning intensity scales to tornadoes whereas random encounter errors are due to lack of damage observation. The uncertainty due to direct classification errors is expected to be unbiased, i.e., it is equally likely that a tornado is underscaled as it is overscaled. On the other hand, random encounter errors are due to the lack of damage medium in a tornado path which could subsequently be used for the tornado classification. Therefore, random encounter errors are always associated with underestimating the tornado characteristics. Another source of random encounter errors is that small tornadoes are often undetected in unpopulated areas. As an example, increased public awareness has led to a trend toward increased reporting of weaker tornados in recent years whereas the average number of strong tornadoes reported is basically unchanged (Twisdale and Dunn, 1983). This error would tend to underestimate the rate of occurrence of all tornado intensities but it would overestimate the occurrence rates of higher intensity tornadoes. An attempt has been made in the study by Twisdale and Dunn (1983) to correct the reported tornado data for the above errors.

A tornado hazard model should include the following elements:

- o variation of tornado intensity with occurrence frequency; the frequency of tornado occurrence decreases rapidly with increased intensity.
- o correlation of width and length of damage area; longer tornadoes are usually wider.
- o correlation of area and intensity; stronger tornadoes are usually larger than weaker tornadoes.
- o variation in tornado intensity along the damage path length; tornado intensity varies throughout its life cycle.
- o variation of tornado intensity across the tornado path width.

<u>Tornado Occurrence Rate</u> - As a first step in the bounding analysis, the frequency of occurrence of all tornadoes (regardless of their intensities) at the site should be calculated. The frequency of occurrence of tornadoes at a plant site may be calculated from historical data or from tornado zoning maps. Historical data at a site could be in terms of number of occurrences of tornadoes in the vicinity of the site. If such data are not available, tornado risk regionalization schemes (Figures 4.2-1 and 4.2-2) may be used.

The occurrence rates for each region as classified in Figures 4.2-1 and 4.2-2 are shown in Table 4.2-3 reproduced from Reinhold and Ellingwood.

<u>Tornado Hazard Model</u> - Using a Poisson process for occurrence of tornadoes, the probability of a tornado striking plant structures during time T with a velocity exceeding V* may be written as:

$$P[\text{strike by tornado with } V > V^*] = \nu T \cdot E[V(A_I) > V^*(A_I)] \tag{4.2-1}$$

where ν is the mean arrival rate per unit area per year for the site, $V^*(A_I)$ is the velocity in an area A_I which will be defined below, and $E(\bullet)$ is the expectation operator taken over all tornado parameters.

Figure 4.2-3 (reproduced from Garson, et al, 1974 with permission) shows a rectangular structure with dimensions A and B. Assume that this structure is approached by a tornado that travels at an angle α measured from the side B. Also, let us assume that this tornado travels a distance equal to L and the damage is limited to width W during the lifetime of the tornado. Knowing the above information, one can define an area A_I where any tornado initiated in this area would strike the structure. Here, the point of initiation for the tornado is assumed to be the mid-point of width W, but in general the following results are not dependent on this assumption. The area A_I is shown in the lower part of Figure 4.2-3. Using simple geometry, it is observed that A_I is made up of four distinct regions (Garson et al., 1974).

1. The sum of the areas denoted by T_1 and T_2 is equal to the total tornado damage area WL.
2. The area denoted by P is equal to HL where H is projection of the structure on a line which is perpendicular to the tornado path.
3. The areas denoted by BA_1 and BA_2 sum to the structure area AB.
4. The areas denoted by E_1, E_2, E_3 and E_4 sum to WG where G is the projection of the structure on the tornado path.

Therefore, it is observed that the tornado will strike the structure if it is initiated within an area A_I given by

$$A_I = WL + HL + WG + AB \quad (4.2\text{-}2)$$

The first term in Equation (4.2-2) is the tornado damage area whereas the next two terms indicate an interaction between the tornado and the structure. Finally, the last term in Equation (4.2-2) is the structure's area. Thus, the tornado hazard curves for a site are expected to depend on the structure's size. For typical structures struck by tornadoes, the last two terms in Equation (4.2-2) may be neglected and A_I may be written as:

$$A_I = WL + HL \quad (4.2\text{-}3)$$

where WL is the area for a point structure and HL is the lifeline term which also contributes to the probability of tornado strike. Normally, one would integrate the results over the probability distribution of angle α for all possible tornado strikes. However, angle α may be conservatively chosen such that it would maximize the second term in Equation (4.2-3), i.e., H may be chosen as the maximum projection length of the structure. In the following paragraphs, a matrix formulation for calculating the annual frequency of tornado strikes with $V > V^*$ is presented which accounts for both terms in Equation (4.2-3).

The probabilistic model for calculating tornado hazard curves at the site may be described as follows. The occurrence of tornadoes in this model is assumed to have a Poisson distribution (Equation (4.2-1)), i.e., the probability distribution of tornado inter-arrival times is assumed to be exponential. Given that a tornado has occurred at the site, the conditional probability of the tornado intensity scale (FPP) is then based on historical data. Next, for each tornado intensity scale, one has to determine the average or the expected value of tornado area (WL) and tornado path length (L) which is to be used in Equation (4.2-3). Thus, one can calculate the expected value of area A_I for each tornado intensity scale (FPP). Assuming that the maximum tornado wind velocity for each FPP intensity scale is the mid-point of the velocity scale as reported in Table 4.2-2, the probability of a tornado strike with maximum wind speeds exceeding a given velocity V^* is equivalent to the probability of that tornado being initiated in the area A_I. As an example, an F3 tornado in Table 4.2-2 would correspond to a maximum wind velocity of 182 mph. Also, one can calculate a corresponding A_I area for F3 tornadoes. Therefore, the probability of exceeding 182 mph winds at the site is equivalent to the probability of an F3 tornado occurring in the corresponding A_I at the site. However, the problem is complicated due to the fact that an F3 tornado does not exhibit the same level of damage along its path. A detailed description of the probabilistic model is given in the next paragraphs.

Table 4.2-3 shows the variation of tornado intensity with occurrence for the regions which are identified in Figures 4.2-1 and 4.2-2. The occurrence-intensity (OI) relationships in this table are based on historical data and they have also been corrected for direct classification errors and random encounter errors. Each row of Table 4.2-3 is a vector {OI} which shows the conditional probability of each F-scale intensity tornado given that a tornado has occurred.

As stated previously, each tornado FPP scale is also associated with an area scale, a length scale, and a width scale as shown in Table 4.2-2. For example, an F4 tornado is expected to have a damage area of 1.0 mi^2 to 9.999 mi^2. On the other hand, it is possible for an F4 tornado to have a smaller or a larger damage area. The same statement may be made about the length scale and width scale of tornadoes which are listed in Table 4.2-2. For the present study, one is interested in the expected value of tornado damage area (WL) for each FPP intensity scale. These average areas may be calculated from historical measured damage areas of observed tornadoes, i.e., one has to obtain an area-intensity relationship for tornadoes. Table 4.2-4 (reproduced from Reinhold and Ellingwood, 1982) shows a matrix of area-intensity relationship for all tornadoes. This area-intensity relationship is based on the area and intensity of 10,240 observed tornadoes (Schaefer, et al., 1980). Each row of this table shows the percentages of each F-scale intensity tornado classified according to area classifications in Table 4.2-2. Since F6 tornadoes have not been observed in the past, the last row in Table 4.2-4 represents engineering judgment in assigning area classifications. This matrix shows that the calculated area and wind scales are slightly skewed and that no tornadoes are expected to have areas in the A6 range. Representing the average of area scales in Table 4.2-2 by a vector {AA} and the matrix in Table 4.2-4 by {AIM}, the vector of expected values of areas for each F-scale intensity {AI} may be written as:

$$\{AI\} = \{AIM\} \bullet \{AA\} \qquad (4.2\text{-}4)$$

As an example for Region A, mean tornado areas (mi^2) for each F-scale intensity are obtained as $\{AI\}^T = \{0.30, 0.72, 1.8, 4.3, 8.5, 15.7, 18.9\}$.

Another characteristic of a tornado is that its intensity does not stay constant along its path. As noted previously, an FPP intensity scale is assigned to a tornado based on the most severe observed damage. However, a tornado is usually at its highest intensity only for a fraction of the time that it is active. Figure 4.2-4, reproduced from Reinhold and Ellingwood, shows a hypothetical F4 tornado with variation of intensity along its path. Table 4.2-5, reproduced from Reinhold and Ellingwood, shows a matrix {VWL} for combined variation of tornado intensity along its path length and across its path width. Each column of matrix {VWL} in Table 4.2-5 shows the percentage of each F-scale damage in the area (WL) for a tornado which has been assigned an intensity scale based on the most severe observed damage. As an example, F3 tornadoes are expected to inflict F3 damage on only 2.7 percent of the total damage area. In fact, 61.5 percent of the damage that is inflicted by a F3 tornado is expected to be very light (FO). This matrix was obtained from the analysis of the damage from 149 tornadoes that occurred on April 3 and 4, 1974.

For a point structure where $A_I = WL$ (see Equation 4.2-3), the probability of wind speeds exceeding {V*} at the site may be written as:

$$P[\{V(A_{I,WL})\} > \{V^*\}] = \{VWL\} \bullet \{AI \bullet OI\} \qquad (4.2\text{-}5)$$

where {V*} is taken to be the mid-point of tornado velocity scales as shown in Table 4.2-2, i.e., the left-hand side of Equation (4.2-5), which is the probability of exceedence or F-scale intensities, is also equivalent to the probability of exceedence of the mid-point velocities for F-scale intensities from Table 4.2-2. The matrix {VWL} was described in the above paragraph and {AI • OI} is a vector where its elements are the expected values of tornado areas times the occurrence-intensity rates for the same F-scale intensity. As an example, for F6 tornadoes, the above equation for Region A may be written as:

$$\begin{aligned} P_A[F \geq F_6] &= P_A\ [V(A_{I,WL}) > 349 \text{ mph}] \\ &= 0.001 \times 18.9 \times 0.0013 \qquad (4.2\text{-}6) \\ &= 2.46 \times 10^{-5} \end{aligned}$$

As described previously, there is a second contribution to the probability of the tornado wind speeds exceeding a certain value which arises from the lifeline term in Equation (4.2-3). As shown in Equation (4.2-3), the lifeline term (HL) depends on the tornado length and it is independent of tornado width.

In fact, the effect of tornado width variations on the probability of exceedence was ignored by neglecting the term WG in Equation (4.2-2).

Table 4.2-6, reproduced from Reinhold and Ellingwood, shows a matrix of the intensity-length relationship LIM where each row of the matrix is the fraction of tornadoes with a given F-scale intensity which were observed to have length scales according to Table 4.2-2. This matrix was based on an analysis of 7,953 tornadoes between 1971-1979 (Reinhold and Ellingwood, 1982). The expected value of tornado length for each F-scale intensity tornado {LI} may be computed from:

$$\{LI\} = \{LIM\} \bullet \{LL\} \qquad (4.2\text{-}7)$$

where {LL} is the vector of mid-point length scales from Table 4.2-2. As an example, for Region A a length-intensity vector $\{LI\}^T$ = {1.53, 3.01, 4.76, 9.15, 18.8, 26.9, 30.1} is obtained (miles).

Since a tornado's intensity varies along its length, one needs to establish a relationship between the total length for a given F-scale tornado and the percentages of total length which were observed to have different F-scale intensities. Such a relationship is shown in terms of the matrix of variation of intensity along length {VL} in Table 4.2-7, reproduced from Reinhold and Ellingwood, where each column of the matrix lists the percentages of total tornado length with different F-scale intensities. This matrix was based on 149 tornadoes which occurred on April 3 and 4, 1974.

Thus, the contribution of lifeline term to the probability of exceedence of a wind speed {V*} at a site may be written as

$$P[\{V(A_{I,WH})\}>\{V^*\}] = \{VL\} \bullet \{LI \bullet OI\} \bullet H \qquad (4.2\text{-}8)$$

Again, V* is taken to be the mid-point of velocity scales for each F-scale tornado as shown in Table 4.2-2. The vector {LI • OI}} is obtained by multiplying each term of the length-intensity vector {LI} by the occurrence-intensity vector {OI}. As an example, the contribution of a structure with a characteristic length of H = 1 ft. to the probability of exceedence of F6 tornadoes for Region A is

$$P_A\left[F \geq F6\right] = P_A\left[V\left(A_{I,WH}\right) > 349 \text{ mph}\right]$$

$$= 0.160 \times 30.1 \times 0.0013 \times \frac{1}{5280}$$

$$= 1.19 \times 10^{-6} \tag{4.2-9}$$

Combining the point structure strike probability and the lifeline strike probability and using the Poisson arrivals for tornadoes (Equation (4.2-1)), the annual probability of exceedence for each F-scale velocity may be written as:

$$\{P[F \geq F_i]\} = \{P[V > V_i^*]\} = \nu[\{C_1\} + \{C_2\} \cdot H] \tag{4.2-10}$$

where vectors $\{C_1\}$ and $\{C_2\}$ are obtained from Equations (4.2-5) and (4.2-8). For a site located in Region A, vectors $\{C_1\}$ and $\{C_2\}$ are obtained as:

$$\{C_1\}^T = \{1.28,\ 4.76(E-1),\ 1.52(E-1),\ 3.08(E-2),\ 4.39(E-3),\ 3.66(E-4),\ 2.46(E-5)\}$$

$$\{C_2\}^T = \{2.15(E-4),\ 2.79(E-4),\ 2.69(E-4),\ 1.31(E-4),\ 4.84(E-5),\ 9.31(E-6),\ 1.19(E-6)\}$$

Figure 4.2-5 shows the tornado hazard curves for a site in Region A for lifeline lengths of 100, 300 and 500 feet. The curves in Figure 4.2-5 are developed for a tornado occurrence rate (ν) equal to 4.8×10^{-4}/square mile-year.

<u>Structural Fragilities</u> - Development of tornado hazard curves for a plant site was described in previous paragraphs. Next, one should develop the conditional probability distribution of plant failure given the maximum tornado wind speed. If plant failure is conservatively assumed to occur when any one of the Category I structures fails, the plant fragility is simply equal to the conditional probability of failure for the Category I structure which has the lowest tornado capacity. Calculation of tornado fragility curves for structures is briefly described below.

Development of fragility curves for a probabilistic bounding analysis could be based on plant design criteria. The design basis tornado characteristics are known for Category I structures (Table 4.2-1). However, one should take into account the conservatisms in design codes, material strength specifications, and assumed failure modes, etc. to calculate the median capacity of plant structures (PRA Procedures Guide, USNRC, 1983). For example, a structure which has been designed for a Zone I DBT (Table 4.2-1) is expected to have a minimum wind capacity of 360 mph. Based on site-specific tornado hazard curves, using 360 mph as the plant capacity may result in a negligible contribution of tornadoes to the plant risk. In such cases, there is no need to develop fragility curves for plant structures. On the other hand, if using the design tornado wind speed leads to high tornado risks, then one needs to further calculate structural fragility curves. As an example, one should consider the conservatisms in design code formulas and material strength, etc., which were used to design the structures for a 360 mph wind. In addition, one should estimate the total variability associated with the calculated median capacity. A probability distribution which has been frequently used to model structural fragilities is the lognormal distribution. From the knowledge of median wind capacity and variability in terms of logarithmic standard deviations, the fragility of plant structures is completely defined. The probability of plant failure (core damage) due to tornadoes is expressed as:

$$P_{f,t} = \int_V P\left|C_i < R_i \mid V = \nu\right| f_V(v)\,dv \tag{4.2-11}$$

where C_i is the lowest capacity of Category I structures, R_i is the resistance, and ν is a given tornado wind speed. The first term in the above integral represents the plant level fragility and the second term represents the slope of tornado hazard curve, i.e., the second term is the probability density function of tornado wind speeds at a site.

If the above formulation results in negligible risks due to tornadoes, then there is no need to include tornadoes in a detailed PRA external events analysis. On the other hand, if the risk due to tornadoes is found to be significant, then tornadoes should be included in the PRA study.

<u>Tornado Generated Missiles</u> - In previous paragraphs, a methodology for a probabilistic bounding analysis of nuclear plant structures for tornado wind effects was presented. Tornado-generated missiles that could potentially impact plant structures at damaging velocities is another aspect of tornado effects on structures. Plants that are designed for tornado

wind loads are also usually designed for tornado missiles. As an example, Table 4.2-8 shows the recent spectrum of tornado missiles published by the USNRC in the Standard Review Plan (USNRC, 1975). Experience in evaluation of structures for impact loads has shown that if all Category I structures are designed for impact loads, and if all safety related equipment and tanks are protected by reinforced concrete walls which are at least 18" thick, then the probability of damage to the plant which could lead to core damage is extremely small. However, if these conditions are not met, then the probabilistic bounding analysis for tornado generated missiles should be performed as explained in the following paragraphs.

As a first step in a bounding analysis for tornado missiles, capacities of structural walls for different missile impacts should be evaluated. For this purpose, the spectrum of missiles in Table 4.2-8 can be used. The missiles in this table cover a wide variety of potential missiles at a plant site. Missiles A, D, and F in Table 4.2-8 may be classified as deformable missiles whereas missiles B, C and E are nondeformable missiles. Except for missile C, these missiles have vertical velocities of 70 percent of postulated horizontal velocities. Missile C which is used to test barrier openings is assumed to have the same velocity in all directions. Missiles A, B, C, and E are considered at all elevations and missiles D and F are considered at elevations up to 30 feet above grade. Although Table 4.2-8 includes both deformable and nondeformable missiles, test data on deformable missiles (Stephenson, 1976) has shown that utility poles and wood planks are not capable of scabbing reinforced concrete walls. Therefore, only an automobile impact needs to be considered among the deformable missiles. Since an automobile can also be treated as a nondeformable missile by calculating an equivalent missile weight (Report of the ASCE Committee on Impactive and Impulsive Loads, 1980), the following discussion will be limited to nondeformable missile impact.

Based on test data, several formulas have been suggested for nondeformable missile impact on reinforced concrete walls. In all of the studies on missile impact which have been performed to date, it has been concluded that the amount of reinforcement is not an important factor in calculating the scabbing thickness or perforation thickness of a reinforced concrete wall. The most widely used formulas for determination of minimum wall thickness required to prevent scabbing are Chang's formula and the modified National Defense Research Committee (NDRC) formula (Chang, 1981). According to Chang, the scabbing thickness (t_s) of a wall or slab may be calculated by

$$t_s = 2.47 \frac{w^{0.4} V^{0.67}}{d^{0.2} \; {f'_c}^{0.4}} \qquad (4.2\text{-}12)$$

where w = weight of missile (lbs),

V = velocity of missile (ft/sec),

d = missile effective diameter (inches) = $\sqrt{\frac{4A_c}{\pi}}$,

f'_c = ultimate strength of concrete (psi),

A_c = contact area of missile (in^2).

The modified NDRC formula gives the penetration depth, x, of a solid missile as

$$x = \sqrt{4KNWd \left(\frac{V}{1000d}\right)^{1.8}} \qquad \text{for } \frac{x}{d} \le 2.0$$

$$x = \left[KNW \left(\frac{V}{1000d}\right)^{1.8}\right] + d \qquad \text{for } \frac{x}{d} > 2.0 \qquad (4.2\text{-}13)$$

where

$$K = \frac{180}{\sqrt{f'_c}} \quad .$$

N is an empirical constant equal to 0.72 for flat-nosed missiles, 0.84 for blunt-nosed missiles, 1.0 for average bullet nosed missiles, and 1.14 for very sharp missiles. Scabbing thickness is then related to penetration depth as follows:

$$\frac{t_s}{d} = 7.81 \left(\frac{x}{d}\right) - 5.06 \left(\frac{x}{d}\right)^2 \qquad \text{for } \frac{x}{d} \le 0.65$$

$$\frac{t_s}{d} = 2.12 + 1.36 \left(\frac{x}{d}\right) \qquad \text{for } 0.65 > \frac{x}{d} \le 11.75 \qquad (4.2\text{-}14)$$

For the NDRC formula, best results are obtained for pipe missiles when d is the actual outside diameter of the pipe in calculating penetration depth and equal to an effective diameter in calculating scabbing thickness.

From the above formulas, one can calculate the minimum tornado missile velocity required to scab the concrete walls and roofs by the spectrum of missiles in Table 4.2-8.

Twisdale and Dunn (1981) have performed simulation studies using the TORMIS Code for typical nuclear power plants to obtain tornado missile impact probabilities and probability distribution of missile velocities. Their study used a total of 65,500 potential missiles that could be injected from different zones near the plant. Most of these missiles represented objects which would be available during construction of a plant. Therefore, their results should be adjusted for other plants where fewer missiles are available. The study by Twisdale and Dunn (1981) shows that the conditional probability of a high velocity missile impacting any of the Category I structures given a tornado strike at the plant site is on the order of 10^{-2}. Finally, the probability of scabbing due to tornado missiles may be written as

$$P[S] = P[TS] \bullet P[MI|TS] \bullet P[S|MI] \qquad (4.2\text{-}15)$$

where S = scabbing, TS = tornado strike, and MI = missile impact. P[TS] is the probability of a tornado strike which is capable of injecting and transporting potential missiles at the plant site. P[MI|TS] can be estimated from the study by Twisdale and Dunn (1981) and P[S|MI] may be conservatively assumed to be 1.0 for a missile which impacts a wall at the minimum speed required to initiate scabbing.

<u>Bounding Analysis Based on System Considerations</u> - If the frequency of a tornado (i.e., tornado loading or tornado missiles) damaging any one of the safety-related structures in the plant is considered to be high (e.g., $>10^{-6}$ per year), an approximate estimate of the tornado-induced core damage frequency can be obtained by developing an event tree for sequences initiated by tornadoes. Figure 4.2-6 is an example of such an event tree for Oconee (reproduced from the Oconee PRA with permission, EPRI, 1984). It models the initiating event (i.e., transient) caused by a tornado and the performance of mitigating systems in a tornado loading environment. A particular core damage sequence is that a tornado has caused loss of offsite power, the reactor trips, main feedwater is lost, emergency feedwater fails, and the safety/relief valve fails to close. High-pressure injection is unavailable due to the tornado failing the borated water storage tank. Table 4.2-9, summarized from the Oconee PRA, gives the other tornado-induced accident sequences. The conditional probabilities of structures housing the initiating

sequences are calculated using the fragility analysis. Structural failure is assumed to occur when the exterior barrier is breached by pressure loading or scabbed by tornado missiles. For more details, see the Oconee PRA and Limerick SARA reports.

4.2.4 Scoping Analysis Procedures

The scoping analysis depends on the location of the plant (site) and its design basis. There are essentially two types of sites from the standpoint of tornado and wind loading: coastal site and inland site. Plants on coastal sites are generally designed to withstand hurricane effects; those on inland sites are designed to resist extreme straight wind loads. Invariably, plants on both types of sites are designed to resist some level of tornado loading. The design bases for different plants vary in the postulation of design basis tornado effects (i.e., speed, pressure drop, and missiles) and selection of extreme wind and hurricane velocities. Also, some essential equipment in certain plants may not have tornado missile protection per current regulatory requirements.

Based on the review of tornado design criteria and the experience gained in the PRA community in performing tornado risk analysis, the following procedures are recommended for scoping analysis:

1. If the plant has been designed against tornado effects, if there are no metal-sided walls or roofs in seismic Category I buildings, if the reinforced concrete walls of seismic Category I buildings are at least 18 in. in thickness, and if there is no non-redundant outdoor unprotected equipment, the contribution of tornado- and extreme wind-induced accidents to the plant risk is judged to be very low. A review of the FSAR and engineering drawings of the plant structures would be necessary for this purpose. If this review shows that the plant meets the above conditions, no further analysis of tornado risks is necessary.

2. If the FSAR review cannot screen out tornado and wind from further analysis, a bounding analysis for tornado risks is done by assuming that structural failure (by pressure loading, pressure drop, and scabbing by tornado missiles) of the exterior barrier of any one of seismic Category I structures leads to unacceptable core damage. Tornado hazard analysis and structural fragility evaluation are to be performed. The results of tornado missile risk studies performed by Twisdale

and Dunn (1981) may be utilized in this bounding analysis. If the frequency of plant damage (i.e., structure) is less than 10^{-7} per year, no further consideration of tornado and extreme wind is needed in the PRA since the conditional probability of core damage is expected to be less than 0.1 in all cases.

3. If the bounding analysis based on failure of any one of the Category I structures cannot be used to screen out tornado and wind from further analysis, consideration of plant systems (accident initiating and mitigating) may be used to obtain a refined estimate of tornado and wind-induced core damage frequency. A simplified event tree is developed to identify important accident sequences. For examples of this approach, see the Limerick SARA and Oconee PRA.

4. If the scoping analysis indicates that the frequency of tornado and wind-induced core damage is higher than 10^{-7} per year, then a detailed analysis of tornado risks is warranted.

Table 4.2-1

Design Basis Tornado Characteristics

Region	Maximum Wind Speed (mph)	Rotational Speed (mph)	Translational Speed (mph)		Radius of Maximum Rotational Speed (feet)	Pressure Drop (psi)	Rate of Pressure Drop (psi/sec)
			Maximum	Minimum			
I	360	290	70	5	150	3.0	2.0
II	300	240	60	5	150	2.25	1.2
III	240	190	50	5	150	1.5	0.6

Reproduced from Regulatory Guide 1.76.

Table 4.2-2

Intensity, Length, Width and Area Scales

Scale No.	Fujita - F Intensity Scale (mph)	Pearson - P Length Scale (mi)	Pearson - P Width Scale (mi)	Area Scale (mi^2)
0	72	1.00	0.010	0.001
1	73-112	1.00-3.15	0.010-0.031	0.001-0.009
2	113-157	3.16-9.99	0.032-0.099	0.010-0.099
3	158-206	10.0-31.5	0.100-0.315	0.100-0.999
4	207-260	31.6-99.9	0.316-0.999	1.000-9.999
5	261-318	100-315	1.00-3.15	10.00-99.99
6	319-380	316-999	3.16-9.99	100.0-999.9

Table 4.2-3

Regional Tornado Occurrence - Intensity Relationships
Corrected for Direct Classification Errors and Random Encounter Errors
(Each Row in the Table is the Vector OI)

Region	F Scale	Corrected Probability of Occurrence at Each F-Scale Intensity						
		F0	F1	F2	F3	F4	F5	F6
Fig. 4.2-1	I	.2227	.3785	.2576	.1016	.0324	.0066	.0009
	II	.3610	.3116	.2198	.0912	.0147	.0015	.0002
	III	.3044	.4421	.1730	.0681	.0112	.0012	.0001
Fig. 4.2-2	A	.1658	.3379	.3122	.1322	.0413	.0093	.0013
	B	.2263	.3527	.2785	.1040	.0312	.0063	.0008
	C	.2830	.3611	.2426	.0856	.0225	.0047	.0006
	D	.3034	.3799	.2436	.0622	.0096	.0011	.0001

Region		Regional Occurrence Rates Corrected for Unreported Tornadoes (occurrences per square mile per year)
Fig. 4.2-1	I	4.12×10^{-4}
	II	2.67×10^{-5}
	III	1.35×10^{-5}
Fig. 4.2-2	A	5.18×10^{-4}
	B	6.98×10^{-4}
	C	3.37×10^{-4}
	D	3.53×10^{-5}

Reproduced from Reinhold and Ellingood 1983.

Table 4.2-4

Intensity-Area Relationship Including Corrections
for Direct Observation and Random Encounter Errors (AIM Matrix)

Actual Maximum Tornado State	Percentage of Tornadoes with Indicated Area Classification					
	A0	A1	A2	A3	A4	A5
F0"	.155	.421	.269	.125	.029	.0016
F1"	.057	.255	.355	.259	.071	.003
F2"	.022	.139	.303	.368	.155	.013
F3"	.009	.070	.210	.376	.289	.046
F4"	.003	.033	.123	.299	.435	.107
F5"	.001	.017	.068	.216	.461	.237
F6"	.001	.012	.049	.185	.458	.295

Reproduced from Reinhold and Ellingwood 1983.

Table 4.2-5

Variation of Tornado Intensity Along Path Length
and Across Path Width (VWL Matrix)

Local Tornado State	True Maximum Tornado State						
	F0"	F1"	F2"	F3"	F4"	F5"	F6"
F0*	1.000	.743	.658	.615	.637	.632	.625
F1*	0	.257	.248	.267	.234	.236	.238
F2*	0	0	.094	.091	.093	.088	.089
F3*	0	0	0	.027	.028	.033	.033
F4*	0	0	0	0	.008	.009	.011
F5*	0	0	0	0	0	.002	.003
F6*	0	0	0	0	0	0	.001

Reproduced from Reinhold and Ellingwood 1983.

Table 4.2-6

Intensity-Length Relationship Including Corrections for Direct Observation and Random Encounter Errors (LIM Matrix)

	Percentage of Tornadoes with Indicated Length Classification					
Actual Maximum Tornado State	PL0	PL1	PL2	PL3	PL4	PL5
F0"	.801	.115	.069	.014	.001	0
F1"	.590	.219	.140	.046	.005	0
F2"	.436	.249	.212	.093	.010	0
F3"	.272	.226	.268	.195	.038	.001
F4"	.141	.152	.272	.326	.090	.019
F5"	.079	.113	.197	.444	.131	.036
F6"	.058	.101	.155	.496	.147	.043

Reproduced from Reinhold and Ellingwood 1983.

Table 4.2-7

Variation of Intensity Along Length
Based on Percentage of Length Per Tornado (VL Matrix)

	Recorded Tornado State						
Local Tornado State	F0	F1	F2	F3	F4	F5	F6
F0	1.000	.383	.180	.077	.130	.118	.100
F1	0	.617	.279	.245	.131	.125	.110
F2	0	0	.541	.310	.248	.162	.120
F3	0	0	0	.368	.234	.236	.160
F4	0	0	0	0	.257	.187	.200
F5	0	0	0	0	0	.172	.150
F6	0	0	0	0	0	0	.160

Reproduced from Reinhold and Ellingwood 1983.

Table 4.2-8

NRC Standard Review Plan Spectrum of Tornado Missile

	Missile	Mass (Kg)	Dimensions (m)	Velocity (m/sec) Region I	Region II	Region III
A	Wood plank	52	.092 x .289 x 3.66	83	70	58
B	6" Sch 40 pipe	130	.168 D x 4.58	52	42	10
C	1" Steel rod	4	.0254D x .915	51	40	8
D	Utility pole	510	.343D x 10.68	55	48	26
E	12" Sch 40 pipe	340	.32 D x 4.58	47	28	7
F	Automobile	1810	5 x 2 x 1.3	59	52	41

Table 4.2-9

Severe Tornado Event Tree Accident Sequences (Oconee PRA)

Sequence	Bin	Frequency	Description
$T_OA\bar{B}CD$	I	1.1-6[a]	Tornado, loss of offsite power, reactor trip and loss of main feedwater, failure of emergency feedwater, failure of SRV to close. HPI unavailable due to tornado failing BWST.
T_OABCD	I	1.1-6	
$T_OA\bar{B}C\bar{D}E$	III	5.0-6	Tornado, loss of offsite power, reactor trip and loss of main feedwater, failure of EFW, successful cycling of SRVs, but failure to obtain ASW feedwater; loss of RCS inventory through cycling relief valves leads to uncovering of core before any significant chance of recovery
T_OABCDE	III	5.0-6	
$T_OAB\bar{C}F$	III	6.5-7	Tornado, loss of offsite power, reactor trip and loss of main feedwater, successful EFW or successful cycling of SRVs and ASW, failure to recover RCS makeup in time to prevent uncovering of the core.
$T_OABC\bar{D}\bar{E}F$	III	5.0-7	

[a]Notation: 1.0-7 = 1.1 x 10^{-7}.

Summarized from the Oconee PRA.

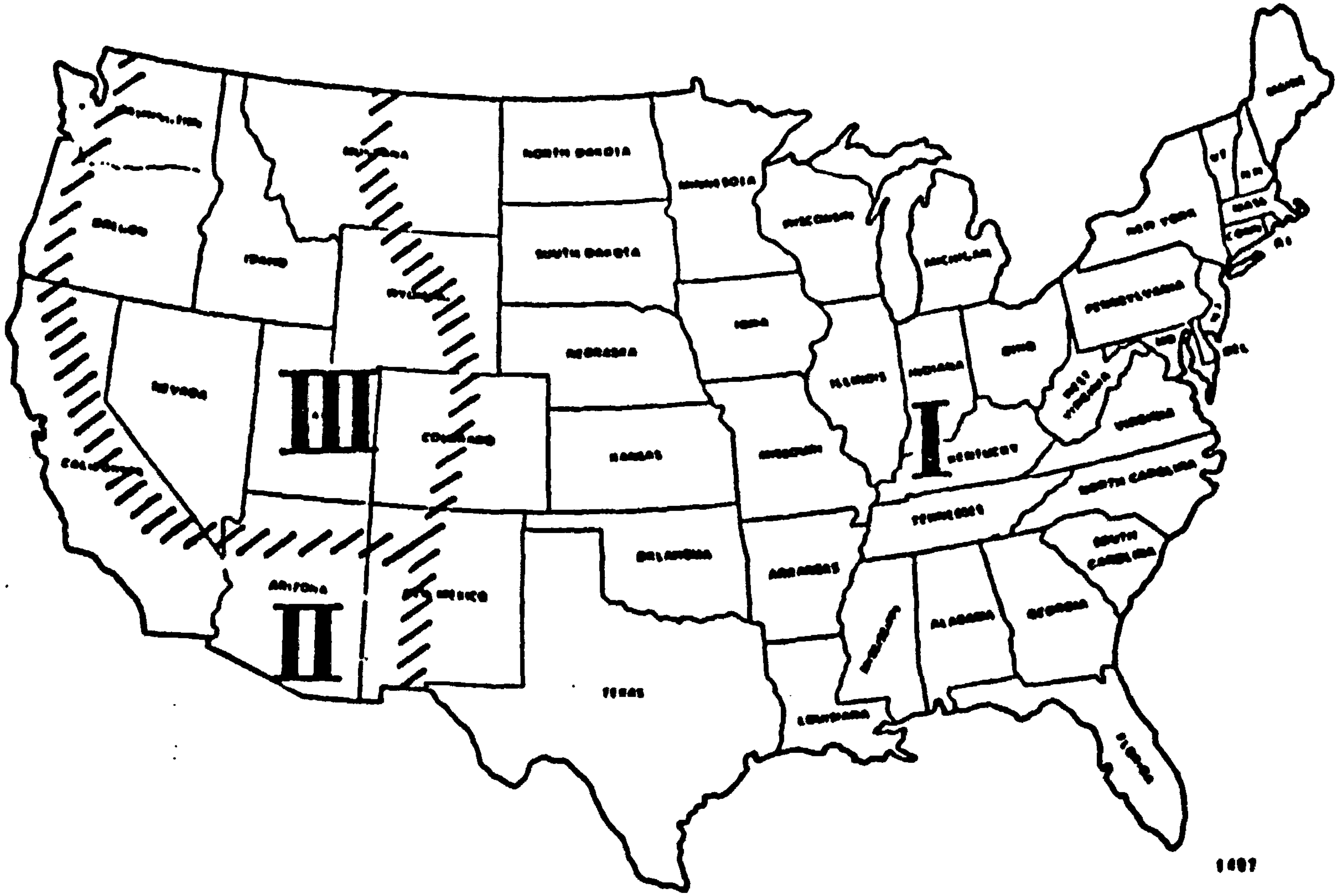


Figure 4.2-1. Tornado Risk Regionalization Scheme Proposed by WASH-1300, Markee, et al. (1975)

Reproduced from Reinhold and Ellingwood, 1983.

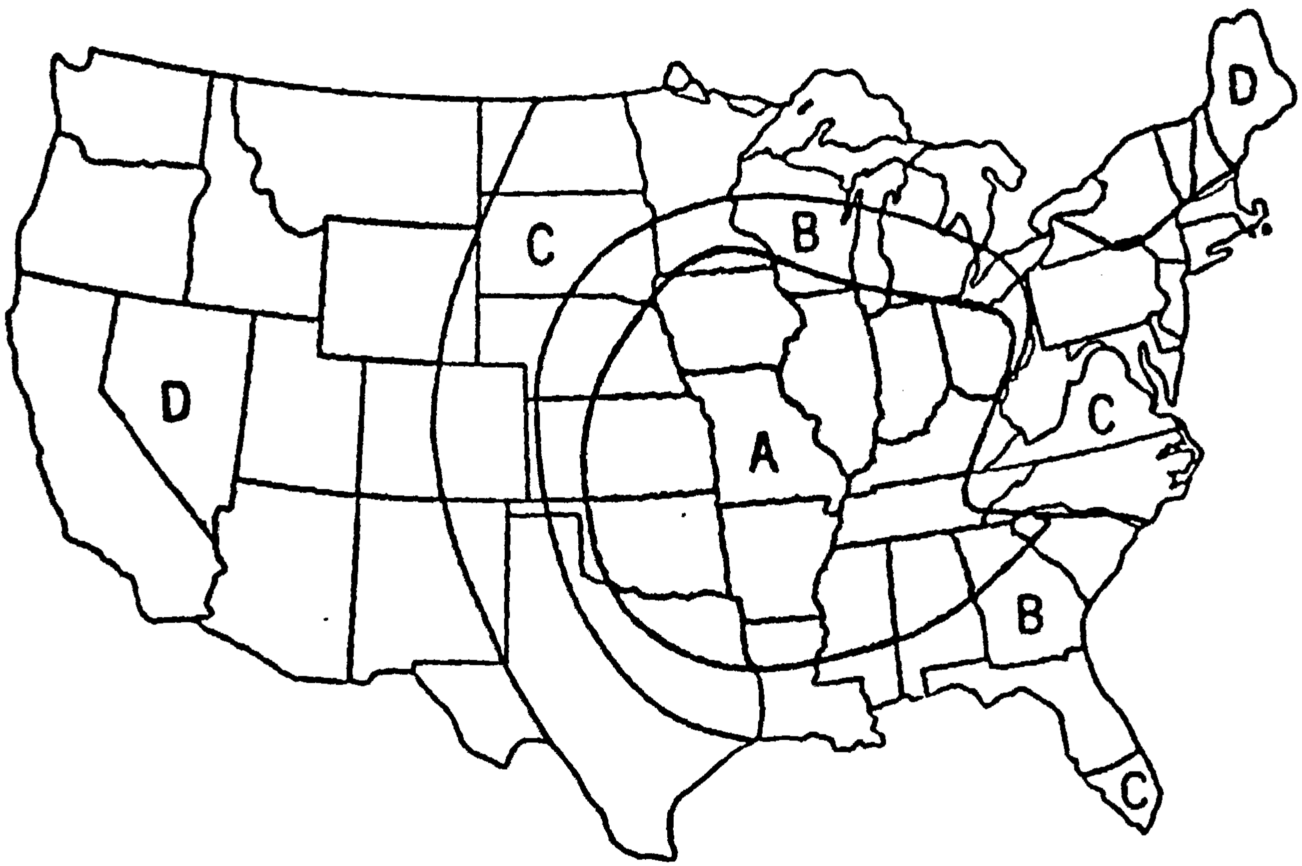


Figure 4.2-2. Tornado Risk Regionalization Scheme Proposed by Twisdale and Dunn (1983) with permission. **Permission to use this copywrighted material was granted by W. R. Sugnet.**

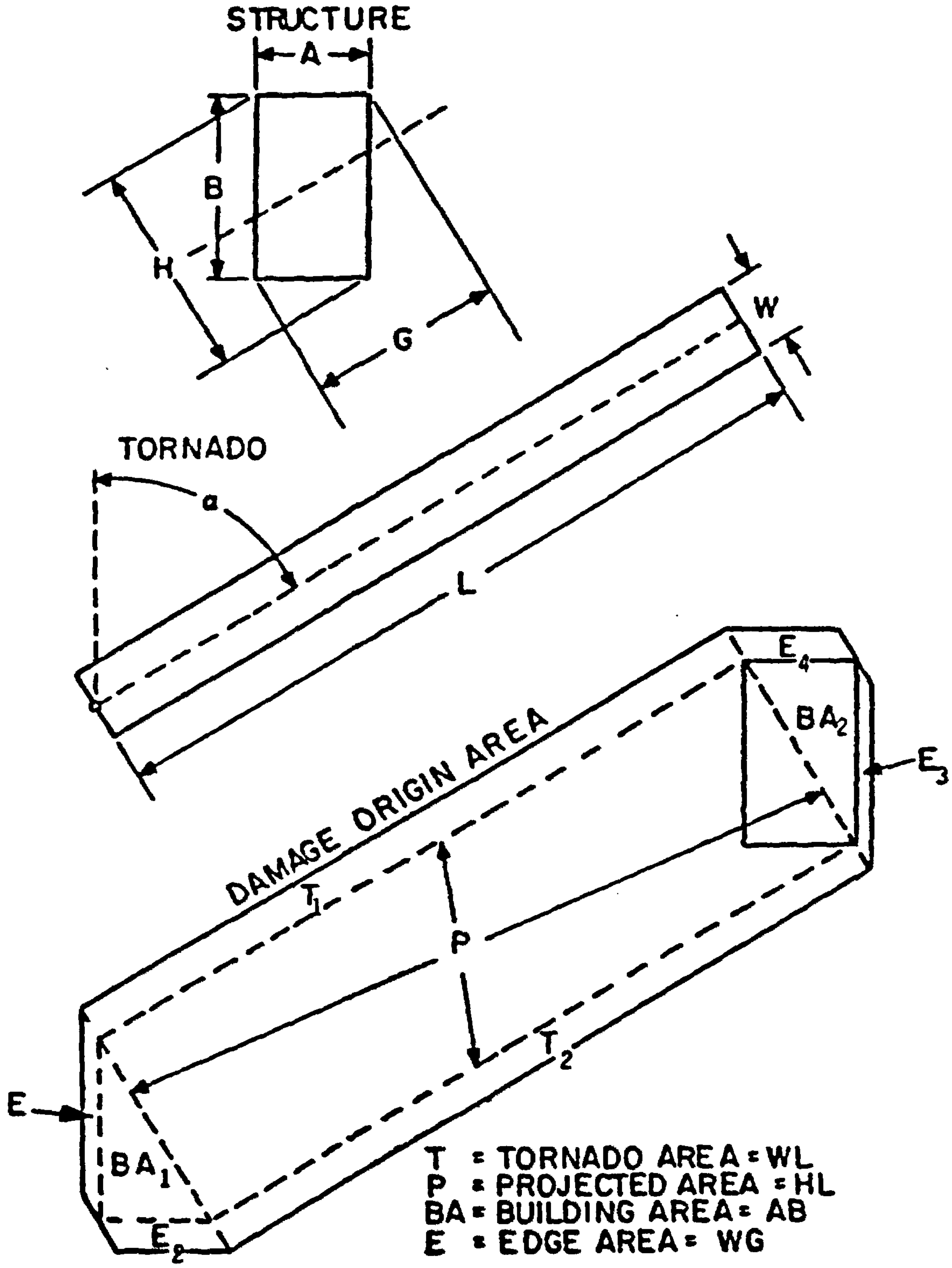


Figure 4.2-3. Tornado Parameters and Damage Origin Area Definition

Reproduced from Reinhold and Ellingwood 1983

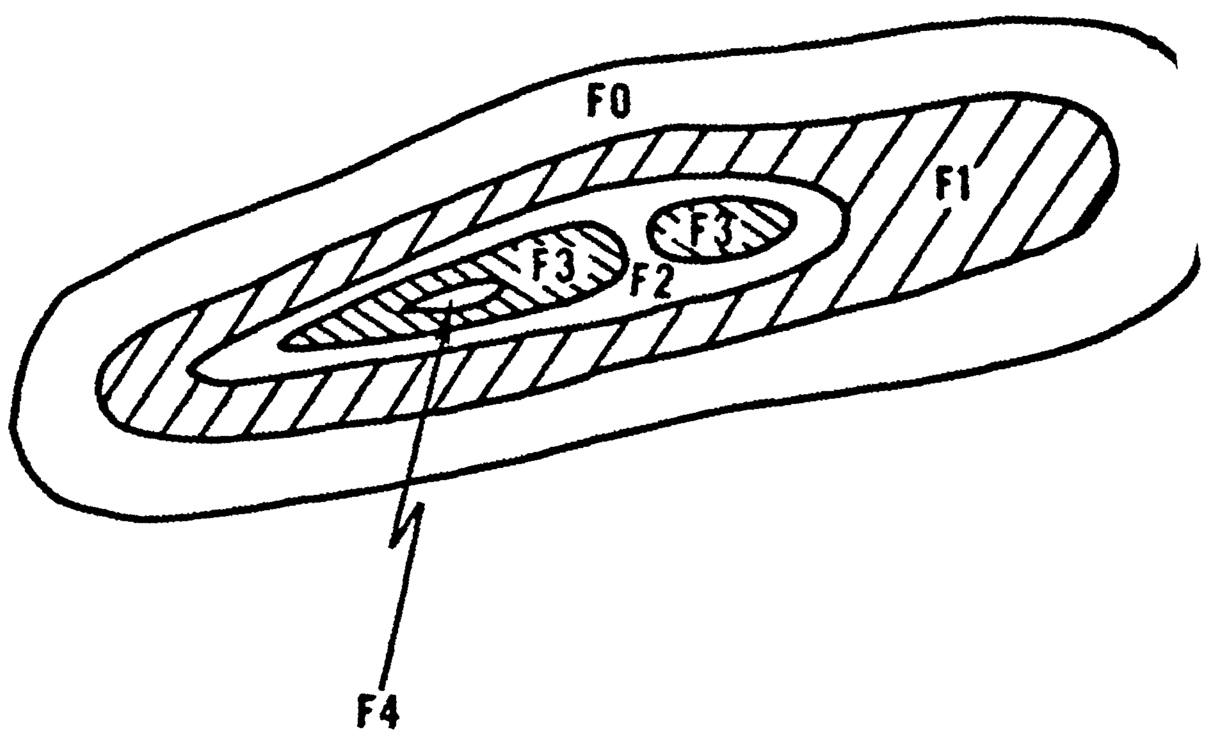


Figure 4.2-4. Sketch of Hypothetical F4 Tornado Illustrating Variation of Intensity

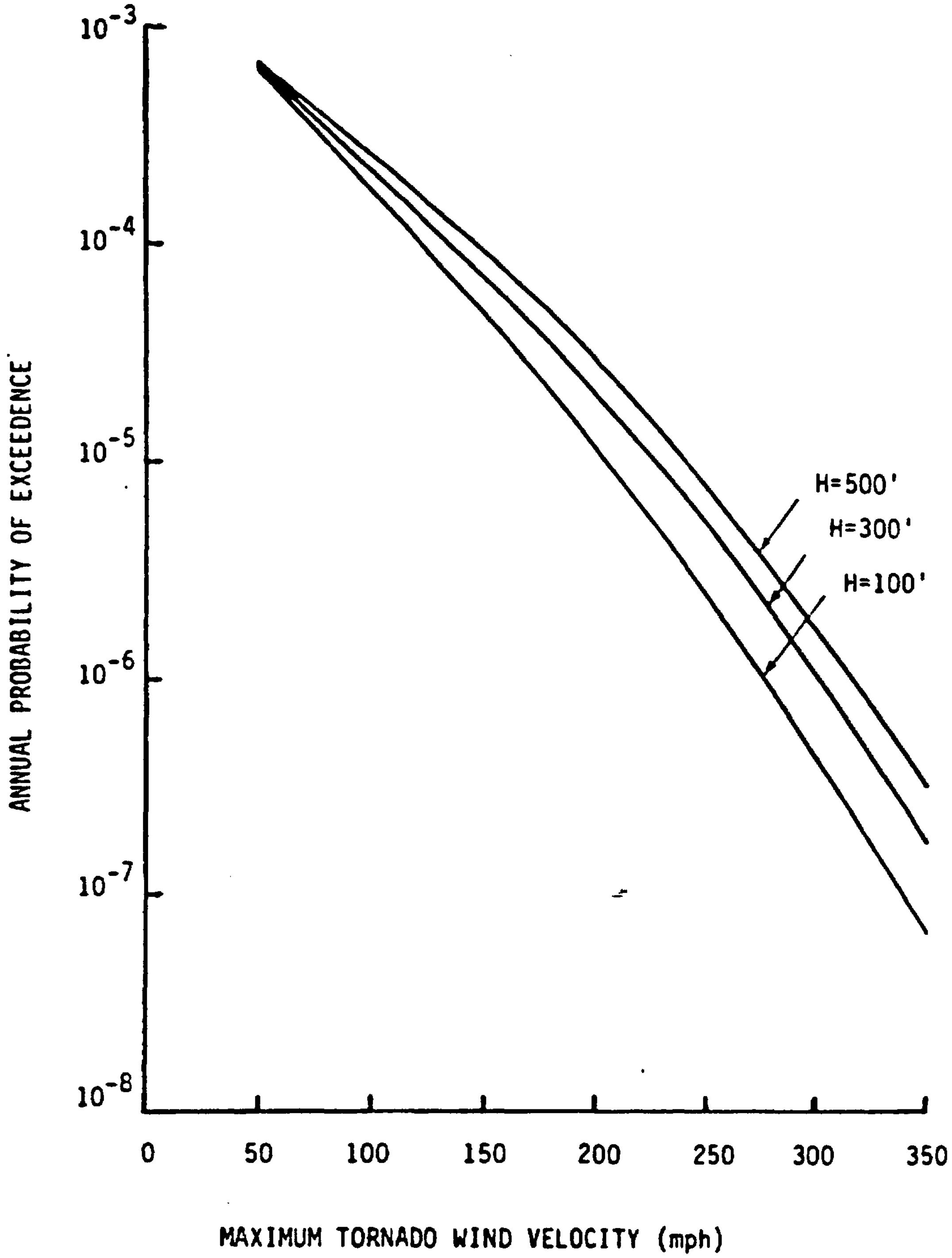


Figure 4.2-5. Typical Tornado Hazard Curves for a Site in Region A

Reproduced from the Oconee PRA with permission.

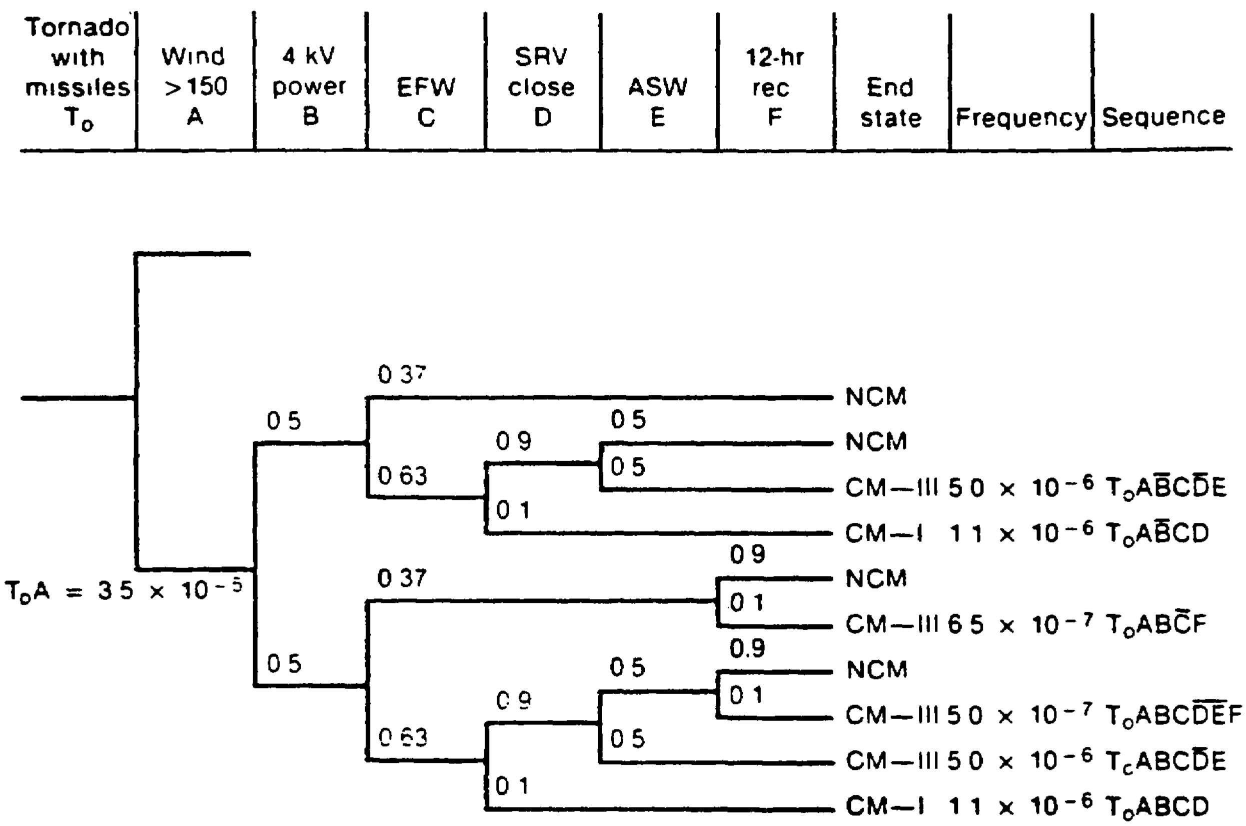


Figure 4.2-6. Event Tree for Sequences Initiated by a Severe Tornado

4.3 Aircraft Impacts

4.3.1 Collection of Information

A nuclear power plant FSAR usually includes a description of airports and aircraft activity near the site. This information includes the locations of commercial airports and private airstrips near the site. Although nuclear power plants are generally built away from major airports, there may be smaller commercial airports or private airstrips in the vicinity of nuclear plants. If a plant is close to a commercial airport, aircraft impact risk may be dominated by the risk due to aircraft landing and take-off accidents. Since the risk due to aircraft landings and take-off accidents is much higher than the risk due to in-flight accidents, a relatively low rate of activity at a commercial airport near a plant site may result in a high contribution to the aircraft risk. In addition to the airports near a site, the Federal Aviation Administration (FAA) airways and military air routes near the site should be identified. If this information is not available in the plant FSAR, it may be obtained from the FAA regional office or the military airbase near the site. The number and size of aircraft using the airports, airways or military air routes should also be obtained.

The probabilistic bounding analysis which is presented in Section 4.3.3 uses accident rates for different types of aircraft, e.g., single-engine, twin-engine, and commercial aircraft. Historical data on aircraft accident rates are available in the FAA Statistical Handbook of Aviation (1979) which is published each year. The same type of data is also available for military aircraft from the Air Force. Also, the probabilistic bounding analysis should account for projected changes in aircraft operations near the site during the plant lifetime.

4.3.2 FSAR Analysis

Aircraft risk is usually considered in a plant FSAR as it relates to meeting the requirements of 10 CFR Part 100 guidelines and the USNRC Standard Review Plan. According to the Standard Review Plan, the probability of aircraft accidents resulting in unacceptable radiological consequences is less than about 10^{-7} per year if the following requirements are met:

1. The plant-to-airport distance D is between 5 and 10 statute miles, and the projected annual numbers of operations is less than $500 * D^2$, or the plant-to-airport distance D is greater than 10 statute miles, and the projected annual number of operations is less than $1000 * D^2$,

2. The plant is at least 5 statute miles from the edge of military training routes, including low-level training routes, except for those associated with a usage greater than 1000 flights per year, or where activities (such as practice bombing) may create an unusual stress situation,

3. The plant is at least 2 statute miles beyond the nearest edge of a federal airway, holding pattern, or approach pattern.

The Standard Review Plan requires that a detailed review of aircraft impact risk be performed if the above requirements are not met or if sufficiently hazardous military activities are identified. Therefore, if the SRP requirements are met in plant design and there are no projected changes to the airports and aircraft activity near plant site, then there would be no need for a probabilistic bounding analysis. In effect, the SRP requirements are judged to be sufficient to insure that the risk due to aircraft accidents remains acceptably low (i.e., less than 10^{-7} per year).

4.3.3 Methods of Bounding Analysis

The following method for bounding analysis for aircraft risks was developed in the Seabrook PSS (1984). In this method, the probability of an aircraft impact on the plant structures may be written as:

$$f_k = \sum_i \sum_j N_{ij} \lambda_j d_j \frac{A_{kj}}{A_{pj}} \qquad (4.3\text{-}1)$$

where

N_{ij} = Number of aircraft operations of type j along airway i,

λ_j = Crash rate of aircraft type j,

d_j = Distance traveled by aircraft type j where the site is within striking distance,

A_{kj} = Crash area of the structures,

A_{pj} = Area where the aircraft may crash.

The term A_{kj}/A_{pj} in Equation 4.3-1 represents the probability of an impact given a crash in the vicinity of the site. This probability and also the distance d_j are determined geometrically. The other variables in the above equation are assigned probability distributions representing the uncertainty in the state of knowledge about their values.

Figure 4.3-1 shows the geometry of an aircraft accident. Assuming that the aircraft is disabled at an elevation h, the distance that it would travel before the crash occurs is gh where g is the glide distance per unit of altitude lost. It may be conservatively assumed that there is an equal probability of crash termination anywhere in the sector of radial length gh and angle $\phi = 180°$ in front of the aircraft. Therefore, A_{pj} is the half circle defined by radius gh where g is the maximum glide ratio which may be assumed to be equal to 17. A_{kj} is the impact area of structures which should include the following:

1. A shadow area of the plant elevation upon the horizontal plane based on the assumed glide ratio for different kinds of aircraft and failure modes.

2. A skid area around the plant as determined by the characteristics of the aircraft under consideration.

3. The areas of those safety-related structures, systems, and components which are susceptible to impact or fire damage as a result of aircraft crashes.

The aircraft impact frequency in Equation (4.3-1) should be calculated for different types of aircraft. Three types of aircraft are identified for these calculations, i.e., single engine, twin engine and commercial aircraft. Also, a fragility analysis may be performed as described below to determine whether these aircraft types are capable of inducing damage to the Category I structures in case of an impact. The fragility calculations are needed only if the probability of impact is greater than 10^{-7} per year, since the conditional probability of core damage is estimated to be less than 0.1.

Capacities of Category I structures against aircraft impact can be determined using the formulas which have been developed for impact of nondeformable missiles on reinforced concrete walls and panels. It may be assumed that the engine and part of the aircraft body represent the nondeformable missile. Information regarding the characteristics of single-engine and twin-engine aircraft may be obtained from Niyogi et al. (1977). Also, it may be conservatively assumed that if an aircraft impacts one of the Category I structures and causes back face scabbing, it would lead to a plant damage state. The formulas which have been developed to predict the minimum scabbing thickness all indicate that the concrete wall thickness required to prevent scabbing is independent of the amount of steel reinforcement for low to moderate steel ratios. Chang's formula (1981) which is based on full-scale and model impact tests of tornado missiles may be used to examine if scabbing occurs. According to Chang, the minimum wall thickness (inches) which is required to prevent scabbing (t_s) is given by Equation (4.2-12).

Although most nuclear power plants in the U.S. have not been designed for any aircraft impact design requirements, design for the spectrum of tornado generated missiles in the USNRC Standard Review Plan provides some structural resistance against aircraft impacts. Typically, if a plant has been designed against an automobile impact as a result of tornadoes, it can withstand a single-engine aircraft impact. Reinforced concrete structures with walls at least 18 inches thick may be excluded from the impact analysis for single-engine aircraft.

4.3.4 Bounding Analysis Based on System Considerations

If the annual frequency of aircraft impacts damaging any one of the safety-related structures is considered to be unacceptably high, a refined estimate of the core damage due to aircraft impacts may be obtained from system considerations. For example, the crash of a general aviation-type aircraft can cause damage to the safety-related equipment which are located outdoors and which have inadequate missile (aircraft) barriers. However, such impacts do not directly lead to core damage. It is discussed in the Seabrook PSS (1982), that the mean annual frequency of refueling water storage tank (RWST) being hit by all types of aircraft is less than 4.3×10^{-8}. Such an impact may cause the operators to trip the plant, but by itself will not produce core damage. With additional system unavailabilities, any resulting scenario has a frequency much smaller than for scenarios involving a transient initiating event (about 13 per year) combined with the unavailability of RWST (about 10^{-7}), which lead to the same plant damage states. Similarly, damage to a diesel generator building by aircraft impact may not lead to core damage since offsite power is also not lost. The loss of the service water system in an aircraft crash accident may not be a significant contributor to the risk if a cooling tower is available as a redundant source.

By this process, the structures housing critical systems whose single failure would lead to core damage or serious release, are identified. The annual frequency of aircraft damage to any one of these structures can be calculated. This frequency is typically less than the value obtained by considering all safety-related structures.

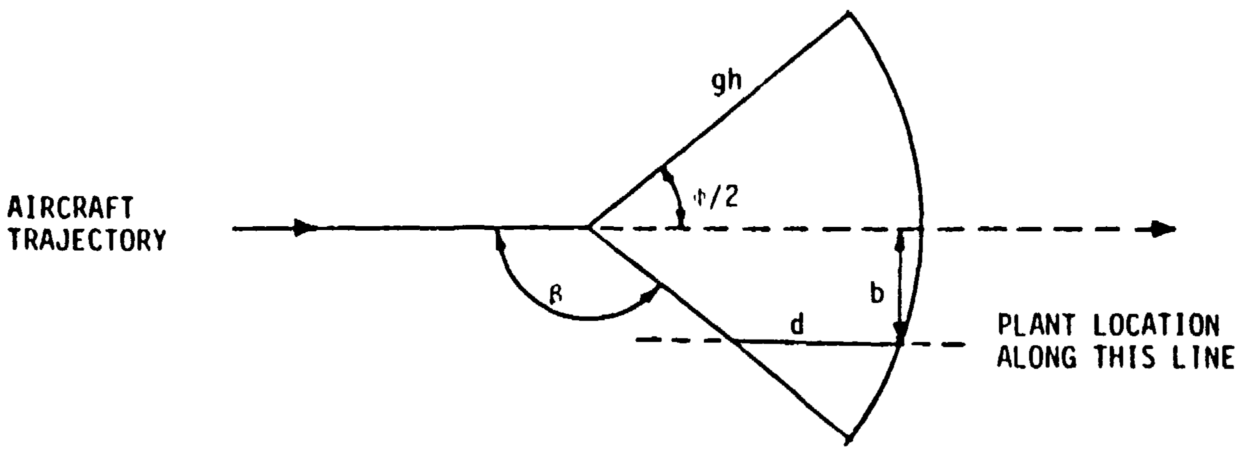


Figure 4.3-1. Geometry for Aircraft Impact Probabilistic Model

4.4 Turbine Missiles

4.4.1 Collection of Information

Failures of large steam turbines in both nuclear and fossil-fueled power plants, although rare, have occurred occasionally in the past. These failures have occurred because of one or more of the following broad classes of reasons: (1) metallurgical and/or design inadequacies, (2) environmental effects, (3) out-of-phase or generator field failures, and (4) failures of overspeed protection systems. The failures have resulted in loss of blades, disk cracking, rotor and disk rupture, and even missiles. Turbine missiles are highly energetic and have the potential to damage safety-related structures housing critical components. Therefore, protection of nuclear power plants from turbine missiles is an important safety consideration. Also, rupture of the turbine casing in a boiling water reactor plant may lead to release of primary coolant steam and radioactivity to the environment. Hence, the plant owners aim to minimize the frequency of turbine failures resulting in casing rupture even if there are no significant turbine missile strikes on safety-related components.

In a total of 2,500 years of turbine operation in nuclear power plants in the free world, only four failures have occurred: Calder Hall (1958), Hinkley Point (1969), Shippingport (1974), and Yankee Rowe (1980). External missiles were produced in the Hinkley Point and Calder Hall failures. Although the causative mechanisms of these failures have been identified and are generally corrected in the modern nuclear turbines, there is no assurance that turbine failures will not occur in the future. Recent discovery of widespread stress corrosion cracking in the disks and rotors of operating nuclear turbines has revived the industry's interest in the issue of turbine failures.

Nuclear plant turbines rotate at 1800 rpm with the low-pressure (LP) and high-pressure (HP) sections on a contiguous shaft. The LP sections have blade hubs (called "wheels" or "disks") shrunk onto the rotor. Depending on the manufacturer and rated capacity of the turbine, there could be 10 to 14 disks on each LP section. The disks are massive components each weighing between 4 and 8 tons. These disks, because of their relatively large radius, are the most highly stressed spinning components in the turbine. With the turbine unit running at less than 120 percent of the rated speed, the disks are stressed well below the yield strength of material so that failures can be caused only by undetected material flaws that may be aggravated by stress corrosion and fatigue. At 180 percent of the rated speed, the disks are stressed at or above their ultimate strength so that they burst into fragments. At intermediate speeds (i.e., 120 to 180 percent), rupture of disks may be caused by a combination of flaws and weaker material in the disks.

Turbine missiles are spinning, irregular fragments with weights in the range of 100 to 8,000 pounds, and velocities in the range of 30 ft/sec to 800 ft/sec. It is conventional to discuss two types of turbine missile trajectories: low trajectory missiles (LTM) and high trajectory missiles (HTM). The low trajectory missiles are those which are ejected from the turbine casing at a low angle toward a barrier protecting an essential system. High trajectory missiles are ejected vertically (almost) upward through the turbine casing and may strike critical targets by falling on them. The customary ballistic distinction between LTM and HTM is the initial elevation angle (ϕ) of the missile (LTM is for $\phi < 45°$ and HTM is for $\phi \geq 45°$). Turbine manufacturers have specified that the maximum deflection angle for the missiles produced in the burst of the last disk on the rotor is 25°. Based on this, the NRC has defined a low trajectory missile strike zone in the Regulatory Guide 1.115 (USNRC) and recommends that the essential systems be located outside this LTM strike zone (Figure 4.4-1). The plants with essential systems outside the LTM strike zone are known to be "favorably oriented" with respect to turbine generators. If a turbine missile impacts a barrier enclosing a safety-related component, interest lies in knowing if the missile perforates or scabs the barrier to cause sufficient damage to the component. Using empirical formulas for scabbing derived on the basis of the full scale and model tests, it is estimated that concrete barriers should be at least 4 feet thick to prevent scabbing. The need for providing such barriers depends on the frequency of turbine failure and the arrangement of safety-related components with respect to turbine missile trajectories. In the design of a nuclear power plant, the designers have many alternative approaches for treating the potential effects of turbine failures (Sliter, Chu and Ravindra, 1983). These approaches can be grouped as: (1) prevention of turbine failure, (2) prevention of missiles, (3) prevention of strike on critical components, and (4) performance of probabilistic analysis to demonstrate that the probability of turbine missile damage is acceptably low.

The information required for a turbine missile probabilistic bounding analysis includes the frequency of missile generation, properties of missiles (i.e., number, weight, area, velocity, and ejection angles), geometry of the plant, thicknesses of roofs and walls of buildings, and locations of safety-related components. The frequency of missile generation can be based on historical data as described in previous paragraphs. From these data, it is concluded that the frequency of missile generation is on the order of 10^{-4} per year. Some turbine vendors have also calculated missile generation frequencies for their turbines as usually lower than the 10^{-4} per year which is based on historical data. However, recent discoveries of stress corrosion cracking (SCC) in nuclear plant turbines suggests that the frequency of turbine missile generation may not be as low as turbine vendors had predicted in the past.

4.4.2 FSAR Analysis

The frequency of serious damage, P_4, from turbine missiles to a specific system in the plant is calculated as (Bush, 1973):

$$P_4 = P_1 P_2 P_3 \qquad (4.4\text{-}1)$$

where:

P_1 = frequency of turbine failure leading to missile generation,

P_2 = probability of missiles striking a barrier that encloses the safety system given that the missile(s) have been generated,

P_3 = probability of unacceptable damage to the system given that one or more missiles strike the barrier.

In practice, the evaluation of P_4 should include consideration of different speed condition, distributions of missiles, and all the safety-related components and systems in the plant.

Turbine missile damage in the older plants was usually considered on the basis of a deterministic safety review according to RG 1.115 and SRP 2.2.3 (NUREG-0800, USNRC, 1975), i.e., the probability of unacceptable damage from turbine missiles (P_4) was implicitly shown to be less than 10^{-7} per year. The new guidelines concerning safety of nuclear power plants against turbine missile strikes are best summarized in NUREG-1068 (USNRC, 1984) which is a review of the Limerick PRA. The following paragraphs have been reproduced from NUREG-1068 describing the NRC position on calculating the probability of turbine missile damage.

"In the past, analyses for construction permit and operating license reviews assumed the frequency of missile generation (P_1) to be approximately 10^{-4} per turbine year, based on the historical failure rate. The strike probability (P_2) was estimated (SRP 3.5.1.3) based on postulated missile sizes, shapes, and energies, and on available plant-specific information such as turbine placement and orientation, number and type of intervening barriers, target geometry, and potential missile trajectories. The damage probability (P_3) was generally assumed to be 1.0. The overall frequency of unacceptable damage to safety-related systems (P_4), which is the sum over all targets of the product of these frequencies, was then evaluated for compliance with the NRC safety objective. This logic places the regulatory emphasis on the strike probability. That is, having established an individual plant safety objective of about 10^{-7} per year, or less, for the probability of unacceptable damage to safety-related systems as a result of turbine missiles, this procedure requires that P_2 P_3 be less than or equal to 10^{-3}.

Although the calculation of strike probability (P_2) is not difficult in principle, for the most part reducing it to a straight-forward ballistics analysis presents a problem in practice. The problem stems from the fact that numerous modeling approximations and simplifying assumptions are required to make tractable the incorporation into acceptable models of available data on the (1) properties of missiles, (2) interactions of missiles with barriers and obstacles, (3) trajectories of missiles as they interact with or perforate (or are deflected by) barriers, and (4) identification and location of safety-related targets. The particular approximations and assumptions made tend to have a large effect on the resulting value of P_2. Similarly, a reasonably accurate specification of the damage probability (P_3) is no simple matter because of difficulty of defining the missile impact energy required to make given safety-related systems unavailable to perform their safety function, and the difficulty of postulating sequences of events that would follow a missile-producing turbine failure.

Because of the uncertainties involved in calculating P_2, the NRC staff concludes that P_2 analyses are "ballpark" or "order of magnitude" type calculations only. Based on simple estimates for a variety of plant layouts, the NRC staff further concludes that the strike and damage probability product can be reasonably taken to fall in a characteristic narrow range that is dependent on the gross features of turbine-generator orientation because (1) for favorably oriented turbine generators, P_2 P_3 tend to lie in the range 10^{-4} to 10^{-3}, and (2) for unfavorably oriented turbine generators, P_2 P_3 tend to lie in the range 10^{-3} to 10^{-2}. For these reasons (and because of weak data, controversial assumptions, and modeling difficulties), in the evaluation of P_4, the NRC staff gives credit for the product of the strike and damage probabilities of 10^{-3} for a favorably oriented turbine and 10^{-2} for an unfavorably oriented turbine, and does not encourage calculations of them. In the opinion of the NRC staff, these values represent where P_2P_3 lie, based on calculations done by the NRC staff and others.

It is the view of the NRC staff that the NRC safety objective with regard to turbine missiles is best expressed in terms of a criterion applied to the missile generation frequency which requires the demonstrated value of turbine missile generation frequency (P_1) be less than 10^{-5} for initial startup and that corrective action be taken to return P_1 to this value if it should become greater than 10^{-5} during operation.

It is the staff's view that the frequency of unacceptable damage to safety-related structures, systems and components as a result of turbine missiles is acceptably low (i.e., less than 10^{-7} per year) provided that the above criterion on turbine missile generation is met. This criterion is to be met by the maintenance of an appropriate in-service inspection and testing program on the turbine throughout the plant's life as discussed in detail in the Limerick SER."

From the preceding paragraphs, it is seen that the emphasis is on turbine maintenance and in-service inspection to assure a value of the frequency of turbine missile generation (P_1) less than 10^{-5} per year. For plants which have favorable turbine orientation and an in-service inspection program, the frequency of turbine missile damage is expected to be less than 10^{-7} per year. Therefore, a probabilistic bounding analysis is not required for these plants. Also, if a plant has an in-service inspection program which assures missile generation frequency of less than 10^{-5} per year, then based on a minimum P_2P_3 value of 10^{-2} per year, turbine missiles can be excluded from external events analysis. For plants which do not have an inspection program but have a favorable turbine orientation, the argument for excluding turbine missiles from further consideration is as follows. Based on historical failure data (Bush, 1973), the probability of turbine missile generation has been calculated to be approximately 10^{-4} per year. Also, Patton, et al. (1983) conducted a comprehensive study which estimated the probabilities of turbine missile generation at operating speed and overspeed as 1.2 x 10^{-4} per year and 0.44 x 10^{-4} per year, respectively. Since damage due to turbine missiles in a favorably oriented turbine is almost entirely due to the high trajectory missiles, the P_2P_3 probability estimate of 10^{-3} per year which was accepted by the NRC staff is judged to be conservative. Therefore, the frequency of turbine missile damage in plants which have favorably oriented turbines is conservatively estimated to be in the order of 10^{-7} per year.

Section 4.4.3 describes the method of bounding analysis which may be used to calculate the annual frequency of damage from turbine missiles. This method may be applied to the plants which have an unfavorably turbine orientation and also do not have in-service inspection for stress corrosion cracking.

4.4.3 Turbine Missile Risk Analysis

A probabilistic bounding analysis for turbine missiles is usually performed in two stages, i.e., the first step is to calculate the probability of missile strike (P_2), and the second step is to calculate the probability of barrier damage P_3. If P_2 P_3 is found to be less than 10^{-3}, then turbine missiles may be excluded from a detailed PRA study. This is based on a P_1 probability of 10^{-4} per year which has been calculated from historical failure data (Bush, 1973). The following paragraphs describe the methodology for a turbine missile bounding analysis. It may be noted that if P_2 is found to be less then 10^{-3} then the analyst may assume P_3 to be equal to 1.0 and still eliminate turbine missiles from an external events PRA study.

<u>Probability of Missile Strike P_2</u> - When the fragments produced in a disk rupture escape the turbine casing, their paths have to be determined in order to know if they intersect barriers protecting essential systems of the nuclear power plant. For this purpose, a description of the parameters of these missiles is needed. Major turbine manufacturers have developed their own - generally proprietary - techniques for assessing whether or not disk fragments exit the turbine casing and the parameters of resulting missiles. By making a set of conservative assumptions regarding the disk breakup mechanism and the impact between the disk fragments and casing structure, they estimate the missile exit conditions. These conditions include weight, cross-sectional areas, shape, size, number of fragments, and exit velocities at different speed conditions.

The probability of a missile striking a barrier is calculated as follows: low trajectory missiles are considered to travel in straight line paths. Their direction is defined in terms of two angles, i.e., the ejection angle, θ_1, from the horizontal plane and the deflection angle θ_2 from the plane of rotation of the ruptured disk (Figure 4.4-2). The angle θ_1, could vary from 0° to 90°. The limits on θ_2 are specified by the turbine manufacturer (e.g., GE specifies -5° to +5° for interior disks and 0° to 25° for end disks). It is customary to assume that the angles θ_1 and θ_2 are distributed uniformly within the specified limits. The probability of a low trajectory missile strike on a structural barrier protecting an essential system is calculated as the ratio of the solid angle the barrier subtends at the missile origin to the total solid angle within which the missile can be ejected out of the turbine casing (GE, 1973).

High trajectory missile strikes are analyzed using ballistic theory (Bush, 1973; General Electric 1973; Semanderes, 1972; Filstein and Ravindra, 1979). The missile is modeled as a point mass experiencing no drag forces. Since the initial velocity of a missile and the ejection and deflection angles are random variables, there is a finite probability that any essential system will be struck by high trajectory missiles. The strike probability density, P_A per unit horizontal strike area, located at a radial distance r from the missile origin is expressed as (Filstein and Ravindra, 1979)

$$P_A = \frac{x_{max}^3 - x_{min}^3}{48\, r^3 g \sin\Delta (V_2 - V_1)} \qquad (4.4\text{-}2)$$

where

$$x_{min} = \frac{rg}{V_2}$$

$$x_{max} = \begin{cases} \dfrac{rg}{V_1} & \text{if} \quad r \le \dfrac{2V_1^2 \sin\Delta}{g \cos\theta_3} \\ rg \sin^2 \cos^{-1} \dfrac{\sin\Delta}{\cos\theta_3} & \text{Otherwise} \end{cases} \qquad (4.4\text{-}3)$$

In the above equations, the missile velocity is assumed to vary between V_1 and V_2; the coordinates of the point along the missile trajectory are (x,y,z) where $x = r\sin\theta_3$ and $y = r\cos\theta_3$. θ_3 is given in terms of θ_1 and θ_2 by

$$\text{Cot}\ \theta_3 = \text{Cot}\ \theta_2 \cdot \text{Cot}\ \theta_1 \qquad (4.4\text{-}4)$$

and g is the acceleration due to gravity.

Twisdale, et al. (1983) have developed a Monte Carlo simulation methodology for tracking the turbine missiles. A six-degree of freedom (6D) model for predicting the free-flight motion of rigid bodies has been formulated. It considers drag, lift, and side forces and simulates missile tumbling by periodic reorientation. A computer code called TURMIS has been developed to integrate the coupled nonlinear ordinary differential equations of motion. Sensitivity studies performed using this sophisticated 6D model clearly support the use of no-drag ballistic model for low-trajectory turbine missile calculations. For high trajectory missiles, the ballistic model introduces prediction errors for individual trajectories, but these errors may not be significant (due to compensating effects of reduced speed and increased impact probability) when statistically averaged for plant risk analysis.

<u>Probability of Barrier Damaged P_3</u> - When a missile impacts a structural barrier (i.e., wall or roof) protecting an essential system, one or more of the following events could take place: penetration, front-face spalling, perforation, or back-face scabbing of the barrier, overall response of the barrier, and ricochet of the missile. All of these events may be important in evaluating the damage potential of turbine missiles. However, local effects of turbine missiles on concrete and steel barriers normally provided in nuclear power plants are particularly important and include penetration, perforation and scabbing. Penetration into a reinforced concrete barrier that does not produce back-face scabbing may not constitute a safety-related damage event unless front-face spalling is of concern. Perforation is the event in which the missile completely penetrates the barrier and continues its flight with a residual velocity less than the initial impact velocity. Scabbing is the failure mode of most interest because the scabbed concrete fragments may damage the enclosed safety-related component or the piping, electrical cable or instrumentation attached to it.

The probability of barrier damage P_3 is calculated using the random properties of the missile (i.e., weight, velocity, impact area, obliquity, and noncollinearity) and empirical impact formulas (Chang, 1981; Berriaud, et al., 1978; Twisdale, et al., 1983). The dispersion in the impact test data about the empirical formulas is used to develop probability density functions of perforation or scabbing thickness. For any given missile impacting a structural barrier of known material and thickness, the probability of perforation or scabbing is calculated using these probability density functions (Twisdale, et al., 1983).

Evaluation of P_2 and P_3 can be done numerically if the missile initial conditions are described by a limited set of parameters and if the plant is assumed to be damaged when the external barrier of a safety-related structure is breached (i.e., perforated or scabbed). In general, turbine missiles are described by a number of random parameters and several barriers separate the safety-related components from the missile sources. A Monte Carlo simulation procedure such as the TURMIS computer code developed by Twisdale et al. (1983) would be needed to handle the multitude of missile trajectories and possible impact conditions encountered in a nuclear plant. The nuclear power plant is modeled for this analysis as follows. A component may be damaged by a missile physically impacting it, or by the missile damaging the electrical cables or piping that are needed for the component to function. Since it is impractical to model all piping, electrical cables and HVAC ducts for the turbine missile analysis, the components may be modeled as being enclosed in fire zones. Each fire zone's boundaries are delineated such that the component and all its support lines (piping, electrical cables, etc.) are within this zone. Therefore, the fire zones are independent of each other. By this technique, the safety-related structures of a plant are divided into a small number of fire zones (at each elevation in the structures and/or through different elevations). The sequences of fire zones which if damaged by missiles in a single turbine failure may lead to core damage or serious release (i.e., "cut sets") are obtained by fault tree analysis (Ravindra, 1982).

Reproduced from Regulatory Guide 1.115.

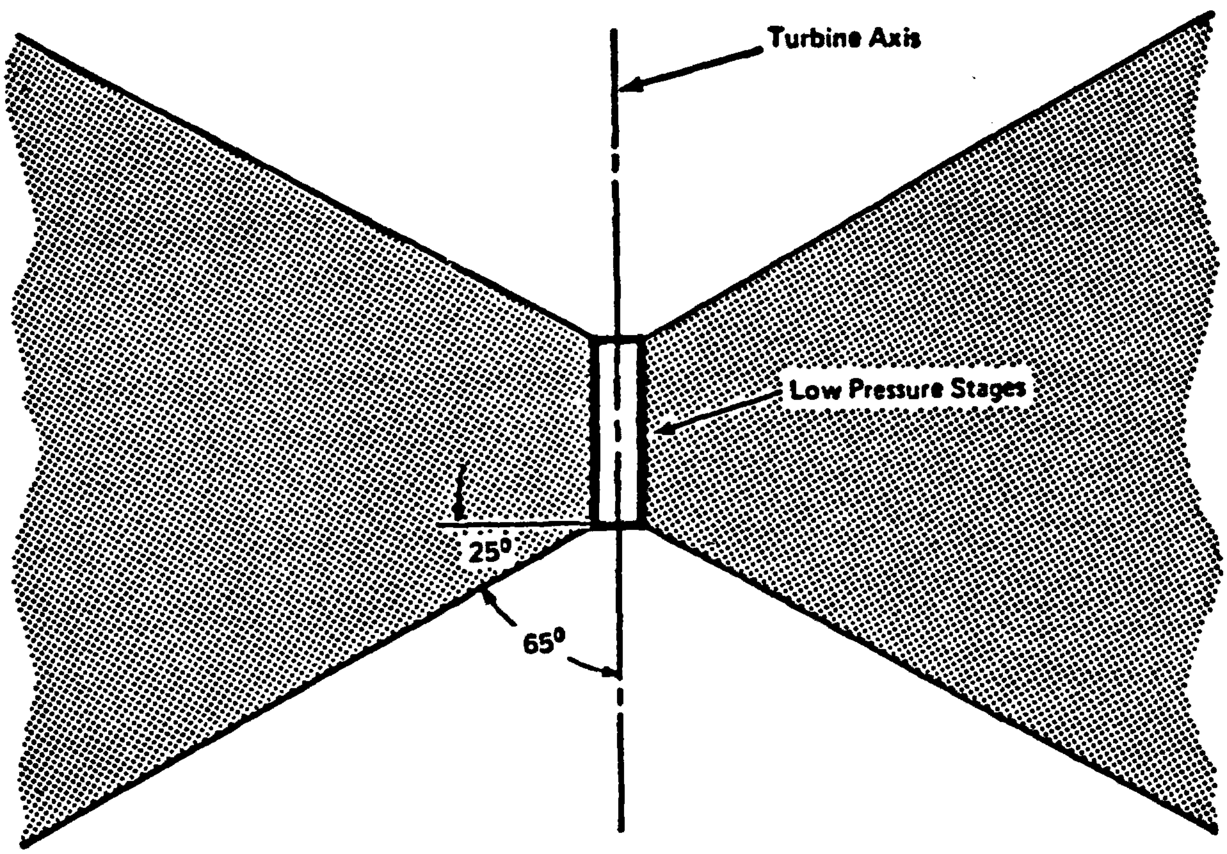
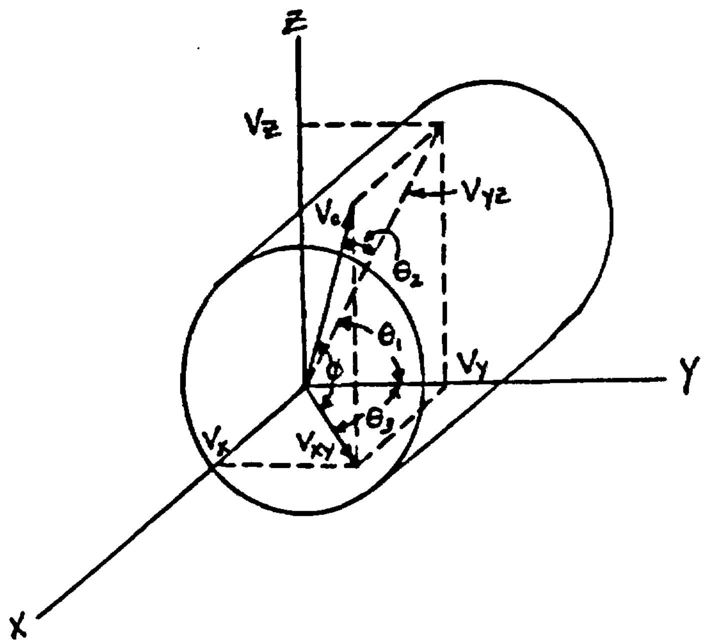


Figure 4.4-1. Low-Trajectory Turbine Missile Strike Zone



V_0 INITIAL VELOCITY

θ_1 ANGLE FROM Y AXIS TO V_{yz}, $0 \leq \theta_1 \leq 90^\circ$

θ_2 ANGLE FROM YZ PLANE TO V_0, $-\Delta \leq \theta_2 \leq \Delta$, $\Delta < 5$ (INNER DISK); $0 \leq \theta_2 \leq \Delta$, $\Delta \leq 25^\circ$ (OUTER DISK)

θ_3 ANGLE ON THE GROUND, $-90^\circ \leq \theta_3 \leq 90^\circ$

ϕ ANGLE FROM GROUND TO V_0, $\theta_2 \rightarrow 0$, THEN $\phi \rightarrow \theta_1$

Figure 4.4-2. Variables and Terminology Used in Calculating Missile Strike Probabilities

4.5 Other External Events

4.5.1 Accidents in Nearby Industrial and Military Facility

The effects of potential accidents in industrial and military facilities in the vicinity of a nuclear power plant include explosion-created overpressure, missiles and thermal effects, and chemical release that may cause the control room to become inhabitable. The topic of chemical release is discussed in Section 4.5.3.

If the facility is located farther than the safe distance defined in Regulatory Guide 1.91, no further analysis of the explosion effects is necessary. Otherwise, a probabilistic bounding analysis similar to that described in Section 4.1.3 should be done to estimate the frequency of core damage induced by industrial and military facility accidents.

4.5.2 Pipeline Accidents

If there are pipelines transporting natural gas, propane or other flammable explosive or toxic gases near the nuclear power plant, a scoping analysis of the hazard posed by the pipelines should be performed.

The annual frequency of failure of a large pipeline near the plant, P_F is calculated as:

$$P_F = N_F D\ f_s\ f_w\ f_t\ f_d / L$$

where

N_F = number of gas transmission line failures per year in the United States,

D = distance of pipe near site (miles),

f_s = fraction of failures that are large,

f_w = fraction of time wind will blow toward plant from pipeline,

f_t = fraction of failures due to construction-related failures and corrosion,

f_d = fraction of leaks going undetected,

L = miles of transmission pipeline in the United States.

In the Indian Point PSS, the frequency is estimated as 4.5×10^{-7} per year. It is judged that the frequency of core damage due to pipeline failure is much lower than 4.5×10^{-7} per year. For further details, see the Indian Point PSS.

4.5.3 Chemical Release

The accidental release of a chemically toxic-vapor cloud from any railroad, highway, or fixed installations in the vicinity of the nuclear power plant could lead to core damage and serious radioactive release to the atmosphere only if the plant operators are affected in such a way that they cannot respond to an emergency when required to do so, or if they are affected in such a way as to set in motion a series of events that lead to damage of the plant. Some of these toxic vapors can be detected by smell (e.g., acetaldehyde, fluorine, hydrogen sulfide, and vinyl acetate); some vapors require automatic detection (e.g., ammonia, vinyl chloride, and phosgene); chlorine is the only vapor for which automatic detection and isolation are required. When the toxic vapor is detected, the operators are expected to don their breathing masks.

In an NRC-sponsored research program, Sandia National Laboratories has studied the principal threats to nuclear power plants from offsite transport or storage accidents involving hazardous materials (Bennett and Finley, 1981; Smith and Bennett, 1980; Bennett and Heath, 1982; Kennedy, Blejwas and Bennett, 1983; Bennett, 1985). The threats include toxic chemical release, overpressure from explosions, and thermal effects from large fires. For offsite accidents releasing large quantities of a toxic material, the concern lies in its potential for incapacitating the control room operators. Smith and Bennett (1980) have developed models to estimate the incapacitation times for arbitrary personnel exposure profiles in terms of exposure concentration and exposure dose. The models are summarized as follows:

1. Concentration dependent - immediate sensory irritant (e.g., chlorine, ammonia).

2. Dual concentration/dose dependency - immediate sensory irritant and/or delayed pulmonary effects (e.g., phosgene, nitrogen dioxide).

3. Dose dependent - related to concentrations exceeding the Threshold Limit Value (e.g., carbon monoxide, styrene).

4. Dose dependent - related to concentrations above an onset level for significant and immediate incapacitating response (e.g., benzene, vinyl chloride).

5. Dose dependent - derived from mortality data (e.g., acetonitrile).

In Bennett and Heath (1982), the probabilities of operator incapacitation given a release along a transportation route near a nuclear plant are estimated for different chemicals. The study considers different dispersion models, types of control room ventilation systems and the effect of chemicals for relatively short exposure durations (e.g., 2 to 5 minutes). The results are presented in terms of the number of shipments of a specific chemical that could pass near the plant such that the probability of operator incapacitation does not exceed certain regulatory guidelines (e.g., 10^{-6} per year). The results also include combinations of various parameters (truck or rail, standoff distance, ventilation system time, exposure duration, and concentration or dose incapacitation). These could be used to perform a scoping quantification study for chemical releases in an external event PRA. Where the particular release event cannot be screened out, further bounding analysis is required as described below:

Figure 4.5-1 is a fault-tree-like representation of toxic-vapor release reproduced from the Limerick SARA. For excessive concentrations of toxic vapor to occur at control room intake, the following events must take place:

1. A release of toxic vapor, and

2. the wind blows from the point of the release toward the plant, and

3. that there is insufficient dilution by the action of atmospheric turbulence, i.e., the plume travel towards the plant and remains above the level of acceptable concentration.

The three possible sources for accidental release of toxic vapors are onsite storage, nearby industrial facilities (e.g., Hooker chemical plant near Limerick), and transportation of chemicals on railroad, river barges and highways.

Given the arrival of toxic gas in excessive concentration at the control-room air intake, there are several possible effects that toxic vapors could have on operators. Figure 4.5-2 illustrates the effect of chlorine on the operators (Limerick SARA). The first branch of the tree asks whether the detection and isolation capability functions as intended. If not, calculations show that the operators will be incapacitated within one minute after the toxic vapor has reached the control room. If the control room is successfully isolated, the operators have about 10 minutes to put on their breathing masks before the chlorine leak incapacitates them. Finally, even if the operators are incapacitated, core damage does not necessarily follow; the reactor may continue to run unattended until relief operators arrive; or, if there is a transient, the reactor will most likely shut itself down.

4.5.3.1 Onsite Storage

Regulatory Guide 1.78 gives the maximum quantities of different chemicals that can be stored onsite at specified distances from the control room based on the leaktightness of the control room. If the quantity stored exceeds the limits of the regulatory guide, automatic detectors have to be installed so that the control room is isolated, should accidental release occur.

If the plant design meets the regulatory guide requirements, it is judged that the probability of chemical release in excessive concentrations combined with the malfunction of the detectors (if any) is very small. In this case, no detailed analysis is needed. If the regulatory guide limits are exceeded, a detailed risk assessment such as that described in the Limerick SARA needs to be performed. The models and methodology developed in the research program at Sandia National Laboratories could be used to estimate the probability of operator incapacitation (see previous references in Section 4.5.3).

4.5.3.2 Offsite Storage and Handling of Chemicals

In this category are included industrial facilities and transportation of chemicals on railroad, river barges, and highways.

Regulatory Guide 1.78 states that if the source of chemical release is situated at a distance greater than 5 miles, its potential impact on the control room habitability needs not be assessed. This is due to the fact that if a release occurs at such a distance, atmospheric dispersion will dilute and disperse the incoming plume to such a degree that there should be sufficient time for the control room operators to take appropriate action.

If the source is located within 5 miles and if the maximum quantity of the chemical stored at the facility or frequency shipped on transportation routes exceeds the R.G. 1.78 limits, further analysis of the risk due to chemical release is needed. Shipments are defined as being frequent if there are 10 per year for truck traffic, 30 per year for rail traffic or 50 per year for barge traffic.

For an example of detailed risk analysis of chemical release-induced accidents, see the Limerick SARA. The results of the research program at the Sandia National Laboratories may be used to estimate the effects of release on control room operators.

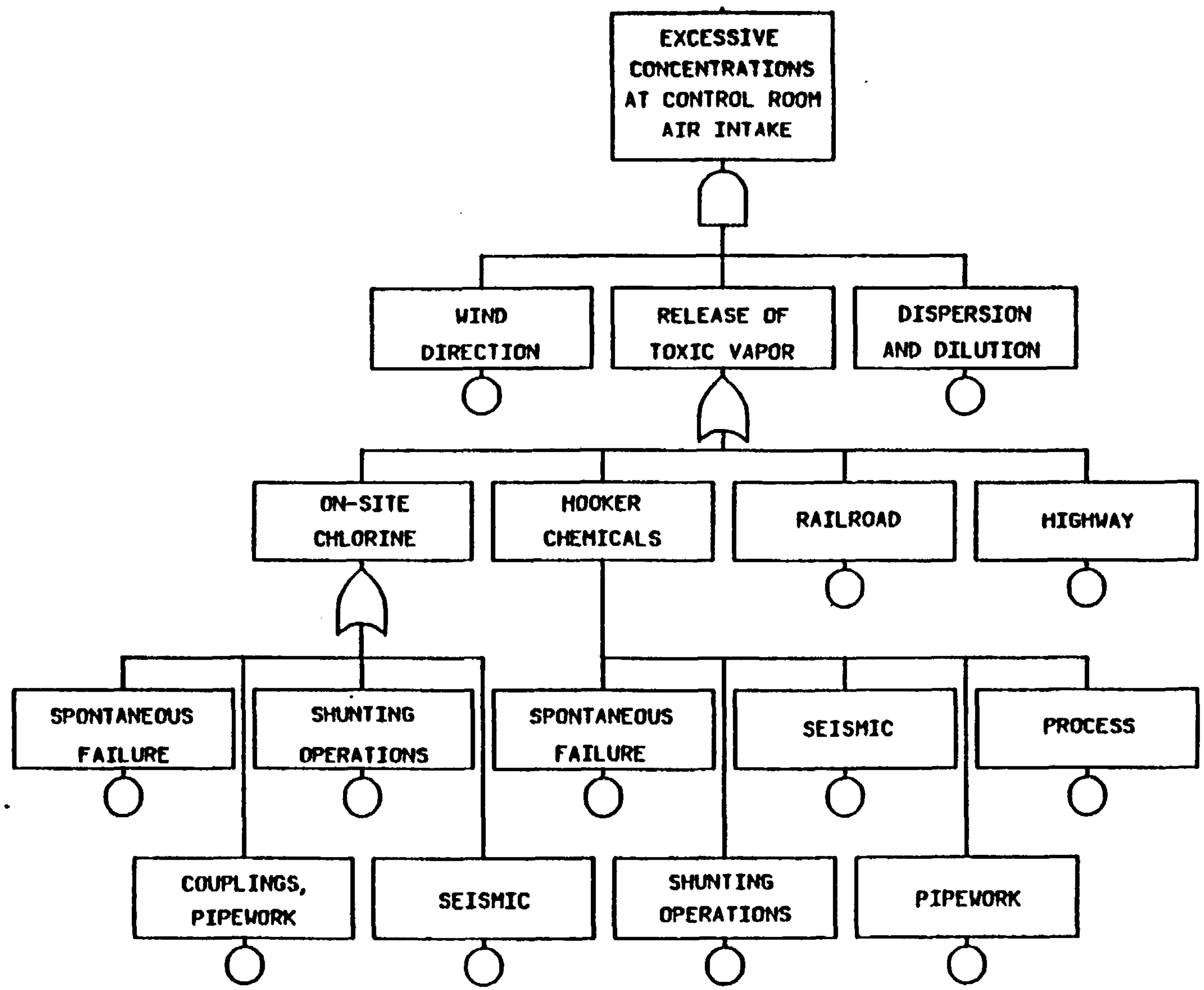


Figure 4.5-1. Fault-Tree-Like Representation of Toxic-Vapor Release

Reproduced from Limerick SARA.

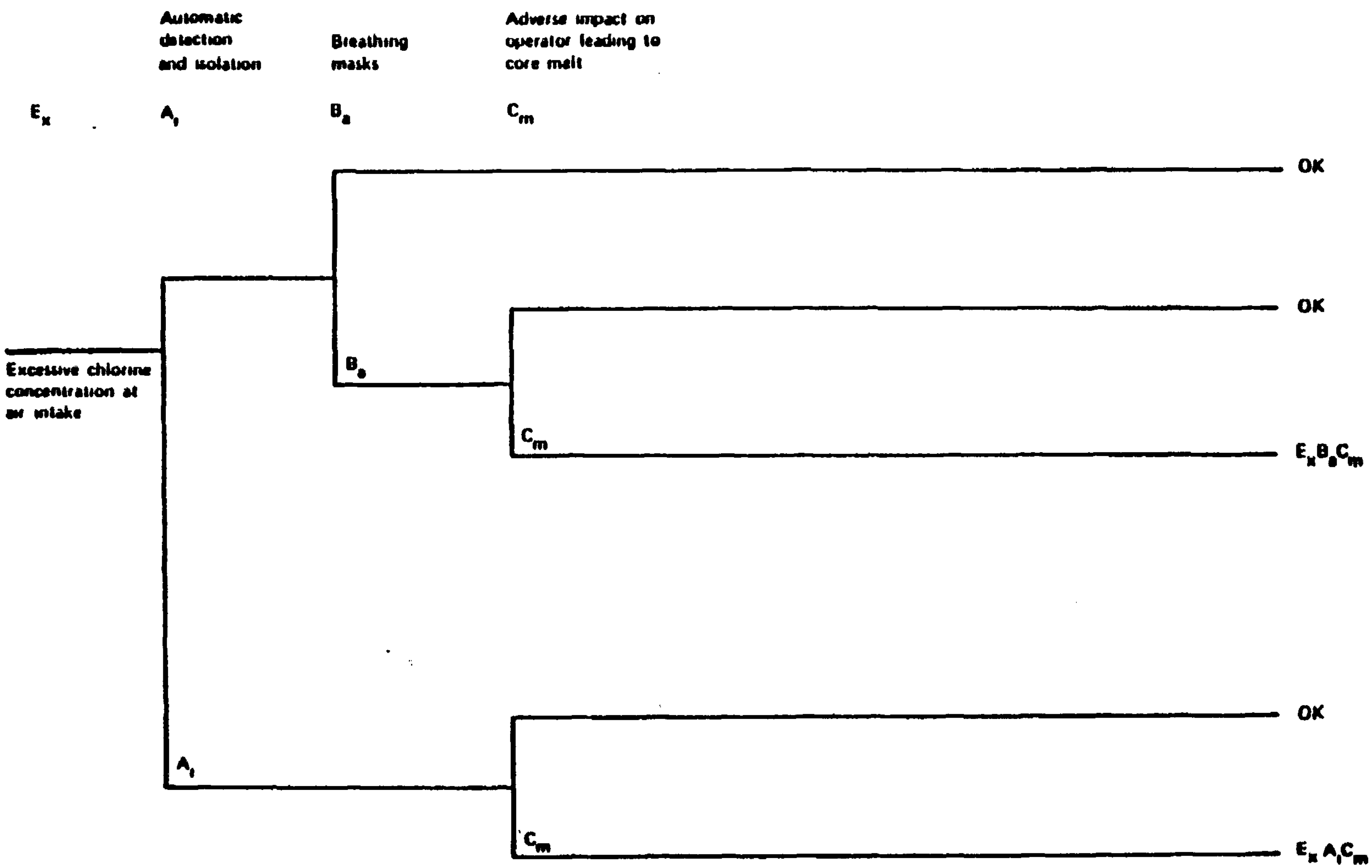


Figure 4.5-2. Event Tree Illustrating Effect of Chlorine on Operators

Reproduced from Limerick SARA.

5.0 SUMMARY AND CONCLUSIONS

In this report, the scoping quantification procedures for external events in probabilistic risk assessments of nuclear power plants are described. External event analysis in a PRA has three important goals:

1. The analysis should be complete in that all events are considered.

2. By following some selected screening criteria, the more significant events are identified for detailed analysis.

3. The selected events are analyzed in depth by taking into account the unique feature of the events: hazard, fragility of structures and equipment, external-event initiated accident sequences, etc.

Based on the above goals, external event analysis may be considered as a three-stage process.

Stage I   Identification and Initial Screening of External Events.

Stage II   Bounding Analysis

Stage III   Detailed Risk Analysis

The scoping quantification methods and the methodology for external event risk analysis have been described in the PRA Procedures Guide (USNRC, 1983). The scoping quantification methods have been applied to the LaSalle County Station in the Risk Methods Integration and Evaluation Program (RMIEP) at Sandia National Laboratories (Ravindra and Banon, 1992). The Procedures Guide and the RMIEP reports also describe procedures for detailed risk analyses of seismic, fire, and flooding initiated events.

In the present report, a review of published PRAs is given to focus on the significance and treatment of external events in full-scope PRAs. Except for seismic, flooding, fire and extreme wind events, the contributions of external events to the plant risks were insignificant. Scoping methods for external events not covered in detail in the Procedures Guide are also provided. For this purpose, bounding analyses for transportation accidents, extreme winds and tornadoes, aircraft impacts, turbine missiles, and chemical release are described.

It is suggested that the PRA analyst and the PRA reviewer use the methods described in this document to augment the methodology discussed in the PRA Procedures Guide.

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11. ABSTRACT (200 words or less)

In this report, the scoping quantification procedures for external events in probabilistic risk assessments of nuclear power plants are described. External event analysis in a PRA has three important goals: (1) The analysis should be complete in that all events are considered; (2) By following some selected screening criteria, the more significant events are identified for detailed analysis; (3) The selected events are analyzed in depth by taking into account the unique features of the events: hazard, fragility of structures and equipment, external-event initiated accident sequences, etc. Based on the above goals, external event analysis may be considered as a three-stage process: Stage I: Identification and Initial Screening of External Events; Stage II: Bounding Analysis; Stage III: Detailed Risk Analysis. In the present report, first, a review of published PRAs is given to focus on the significance and treatment of external events in full-scope PRAs. Except for seismic, flooding, fire, and extreme wind events, the contributions of other external events to plant risk have been found to be negligible. Second, scoping methods for external events not covered in detail in the NRC's PRA Procedures Guide are provided. For this purpose, bounding analyses for transportation accidents, extreme winds and tornadoes, aircraft impacts, turbine missiles, and chemical release are described.

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